In-situ optical testing of exposure tools via localized wavefront curvature sensing

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THE CENTER FOR X-RAY OPTICS

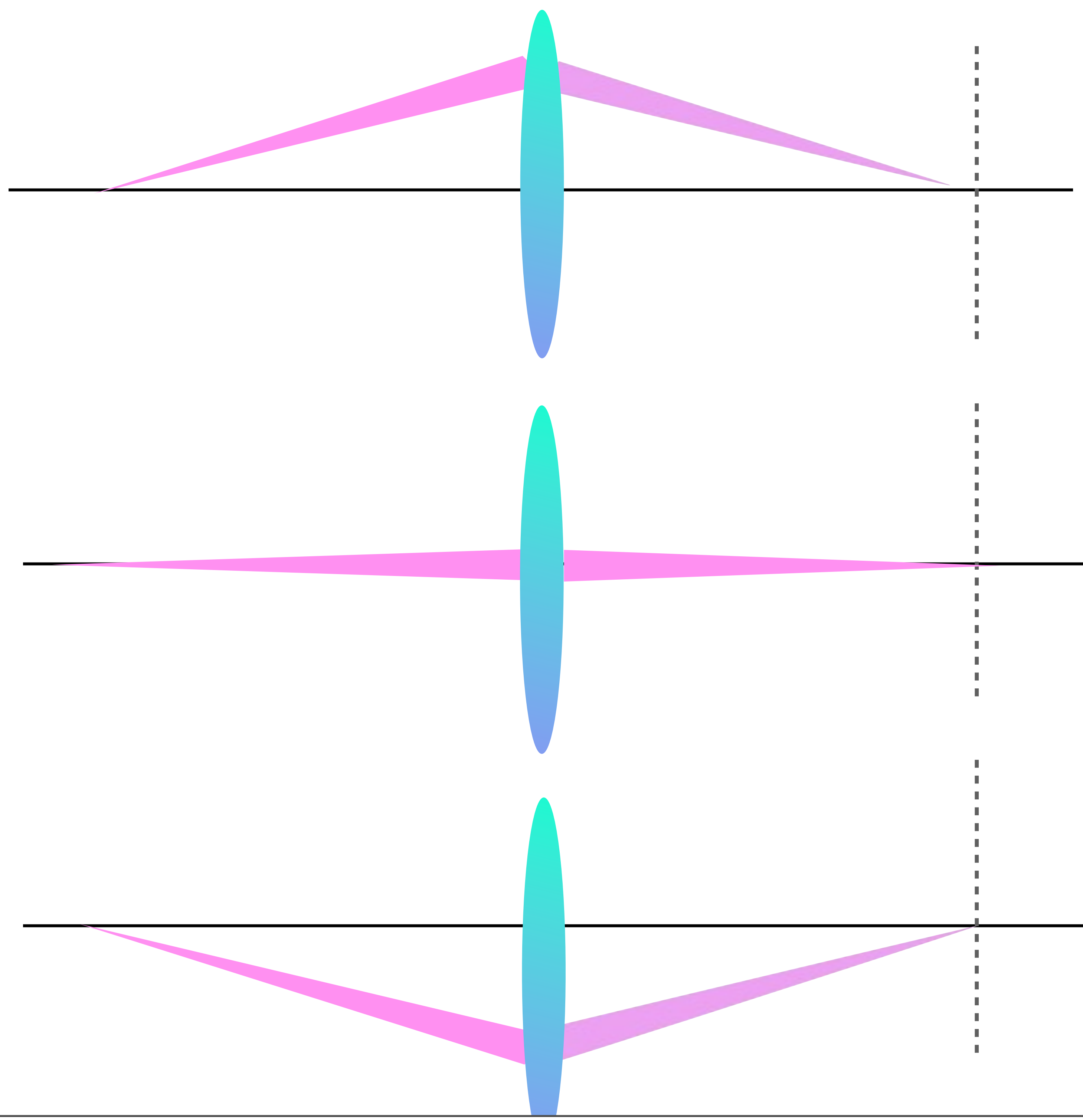
BERKELEY LAB

A new optical test

1. In-situ
2. Non-interferometric
3. Simple integration
4. Scales to high NA (and smaller λ)

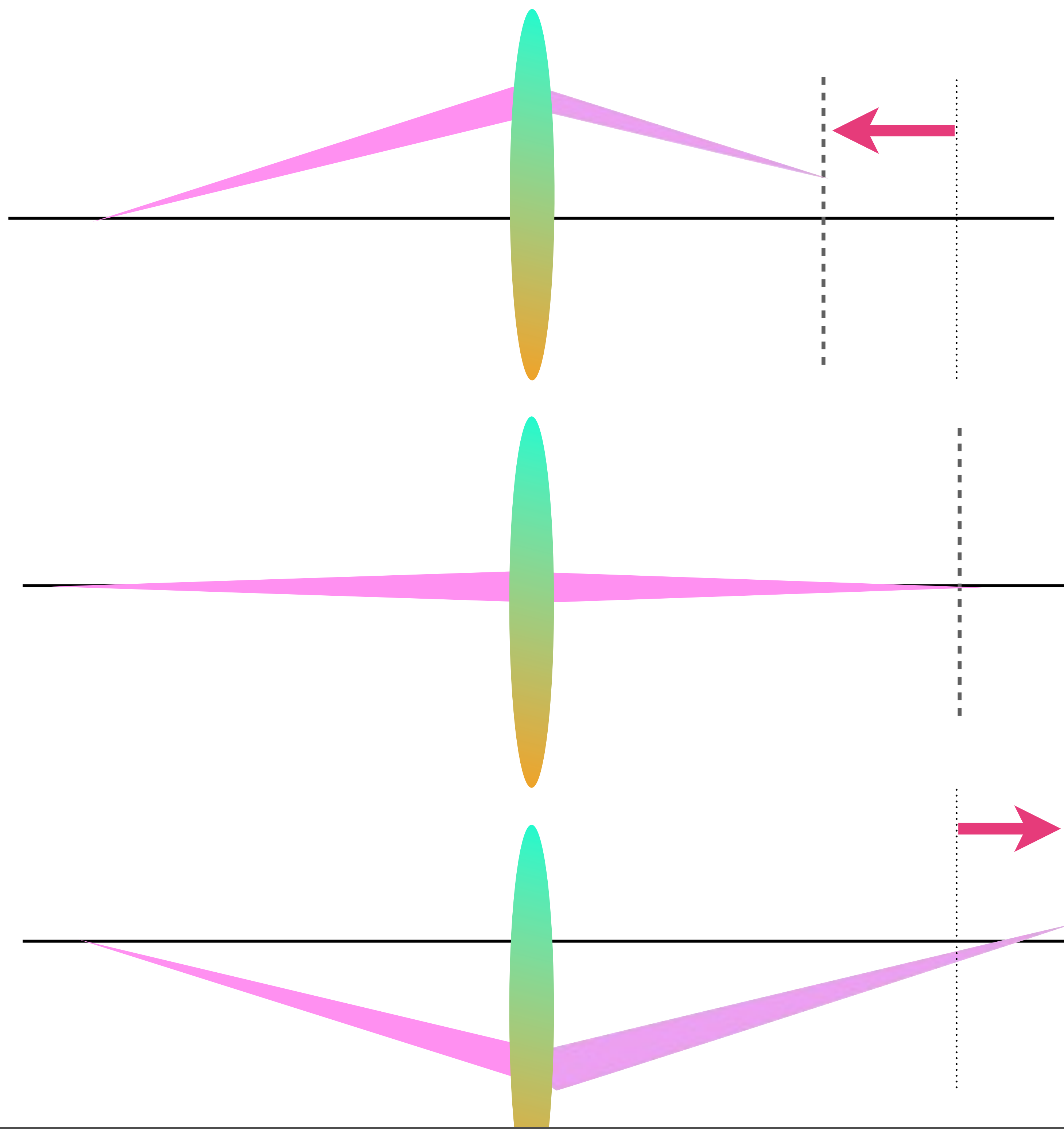
Basic idea: Aberrated optical systems have nonuniform focus signatures over pupil

No aberrations



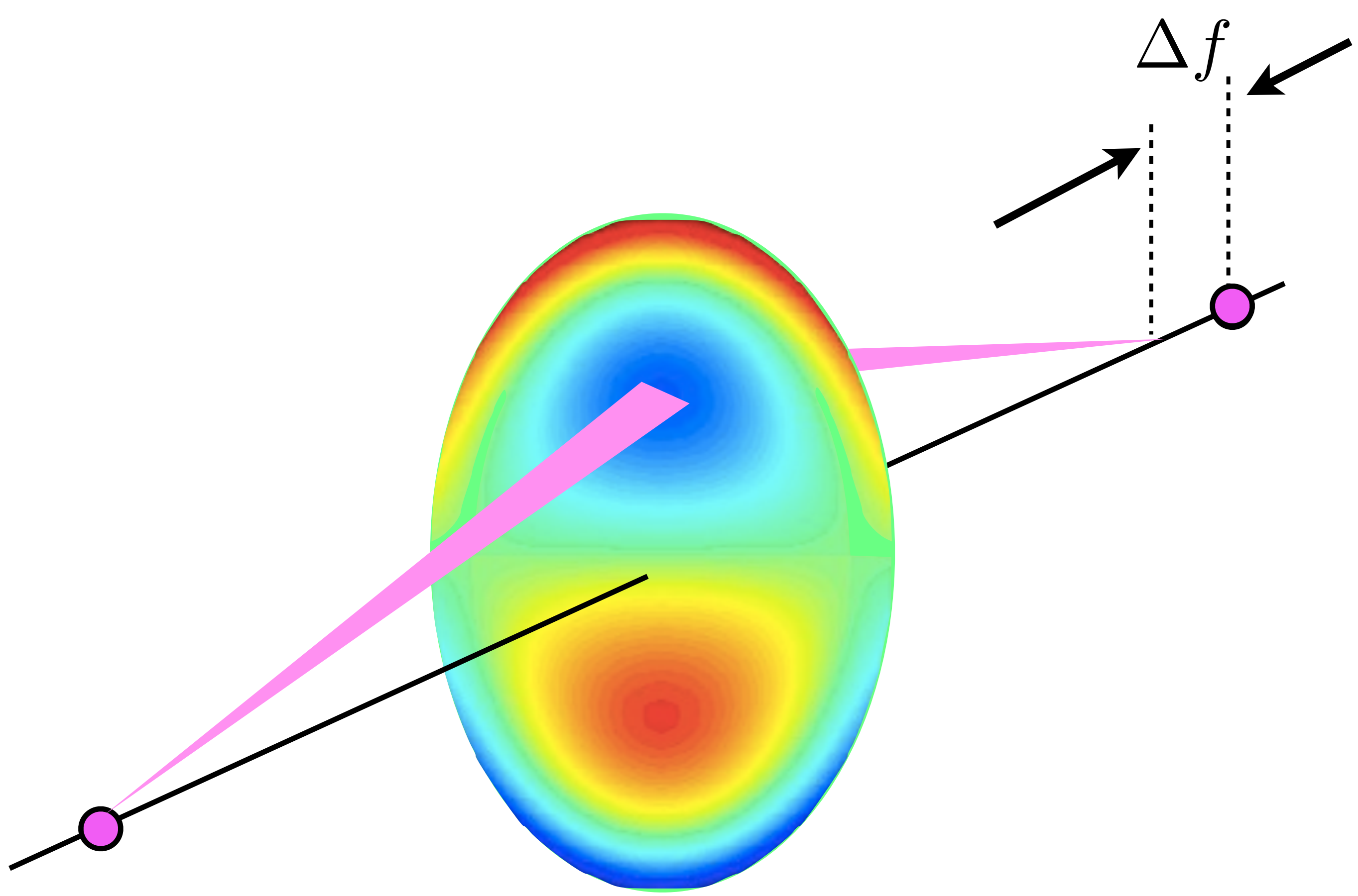
Basic idea: Aberrated optical systems have nonuniform focus signatures over pupil

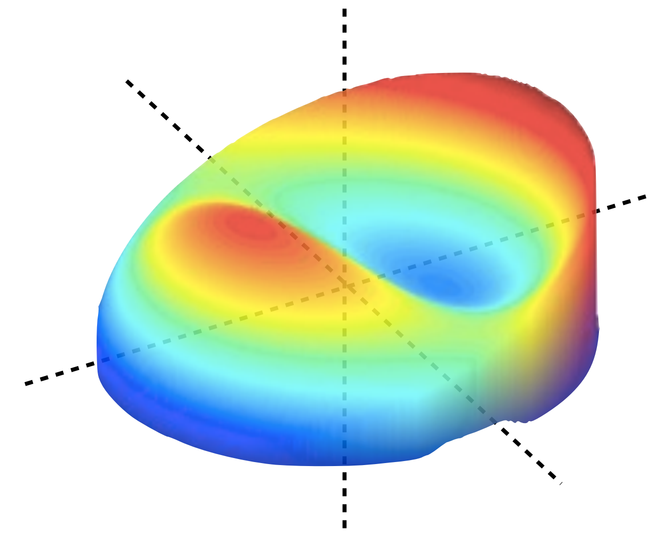
Aberrated



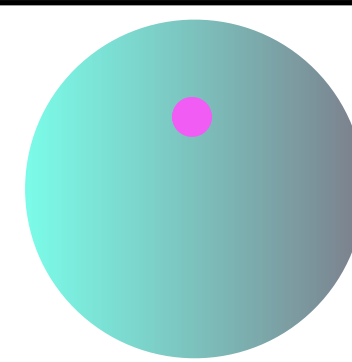
Zernike polynomials have curvature signature

Z6: Coma



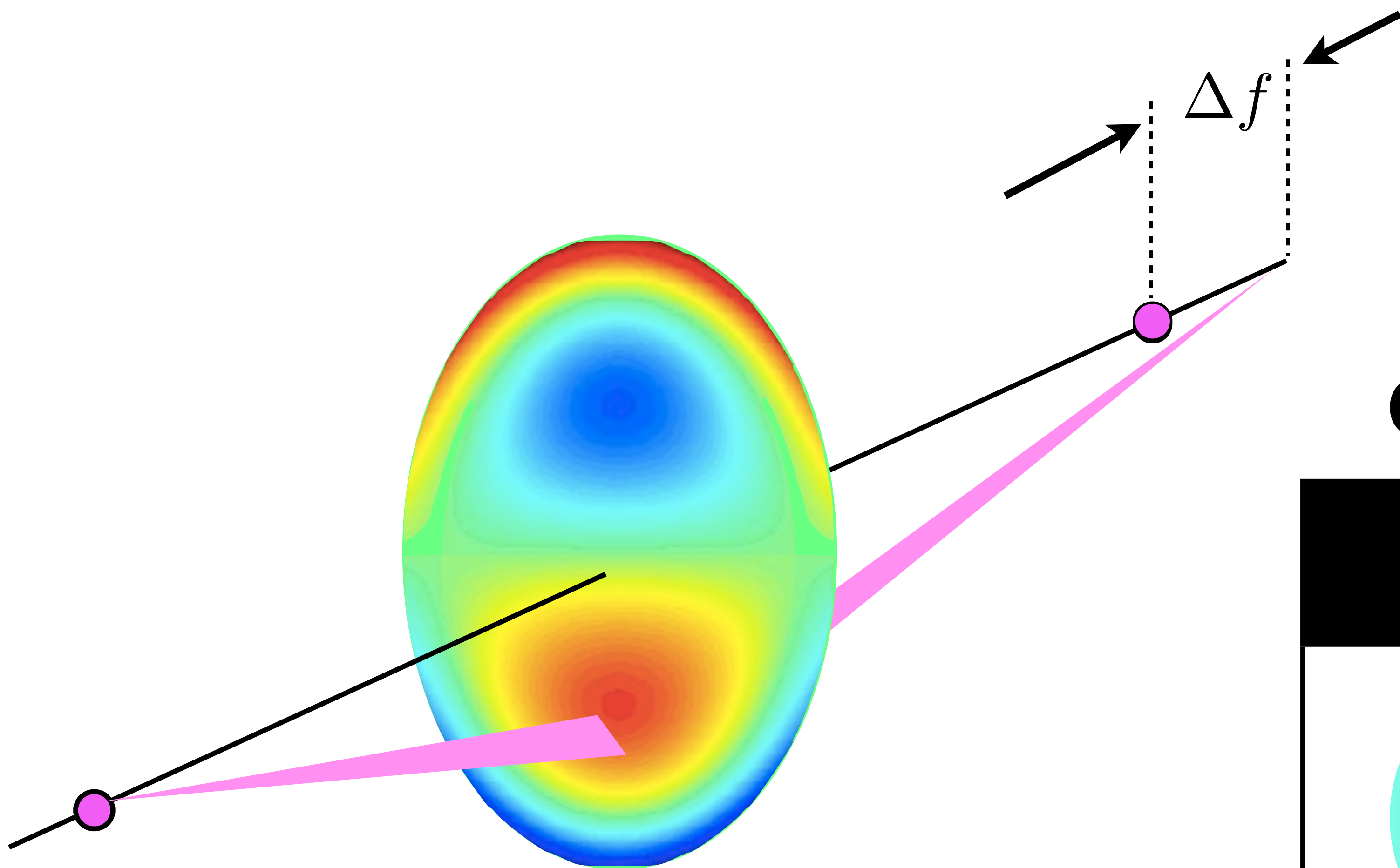


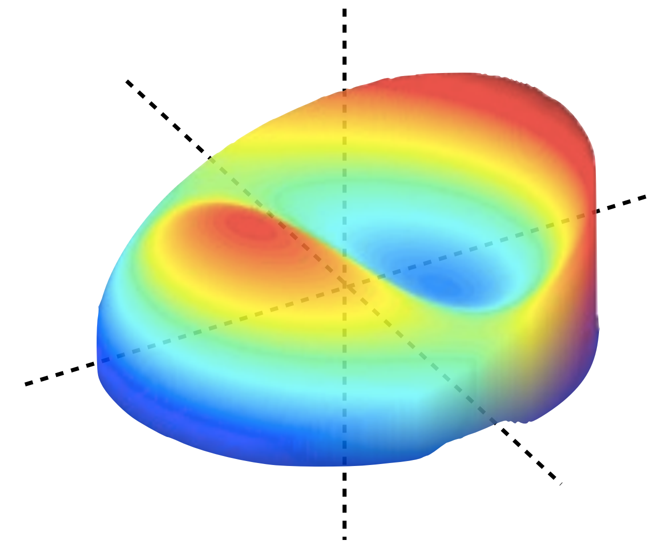
Curvature signature

Probe	Δf
	–

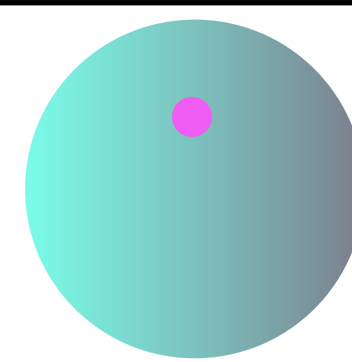
Zernike polynomials have curvature signature

Z6: Coma

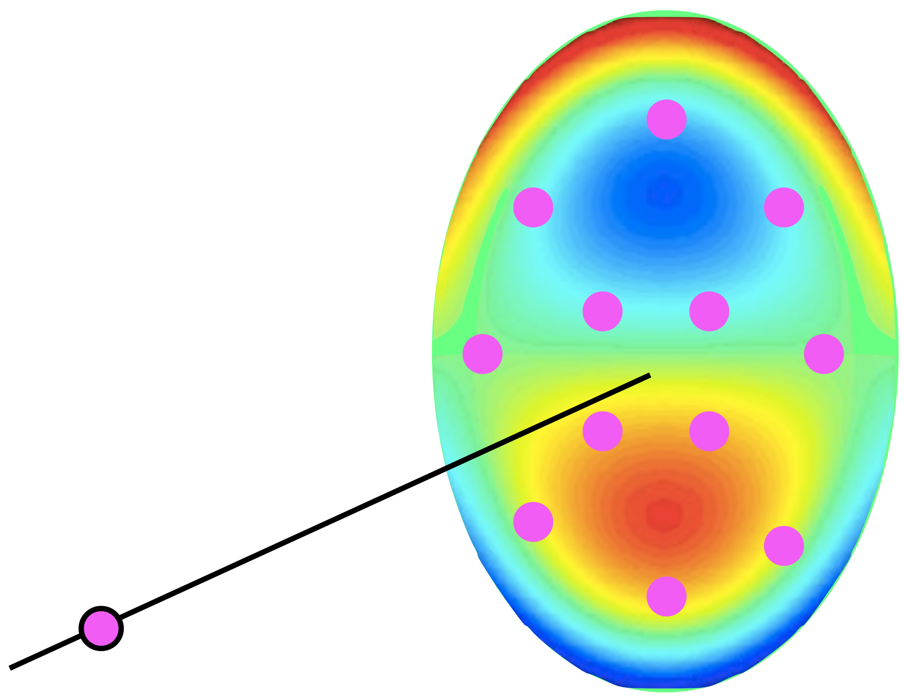




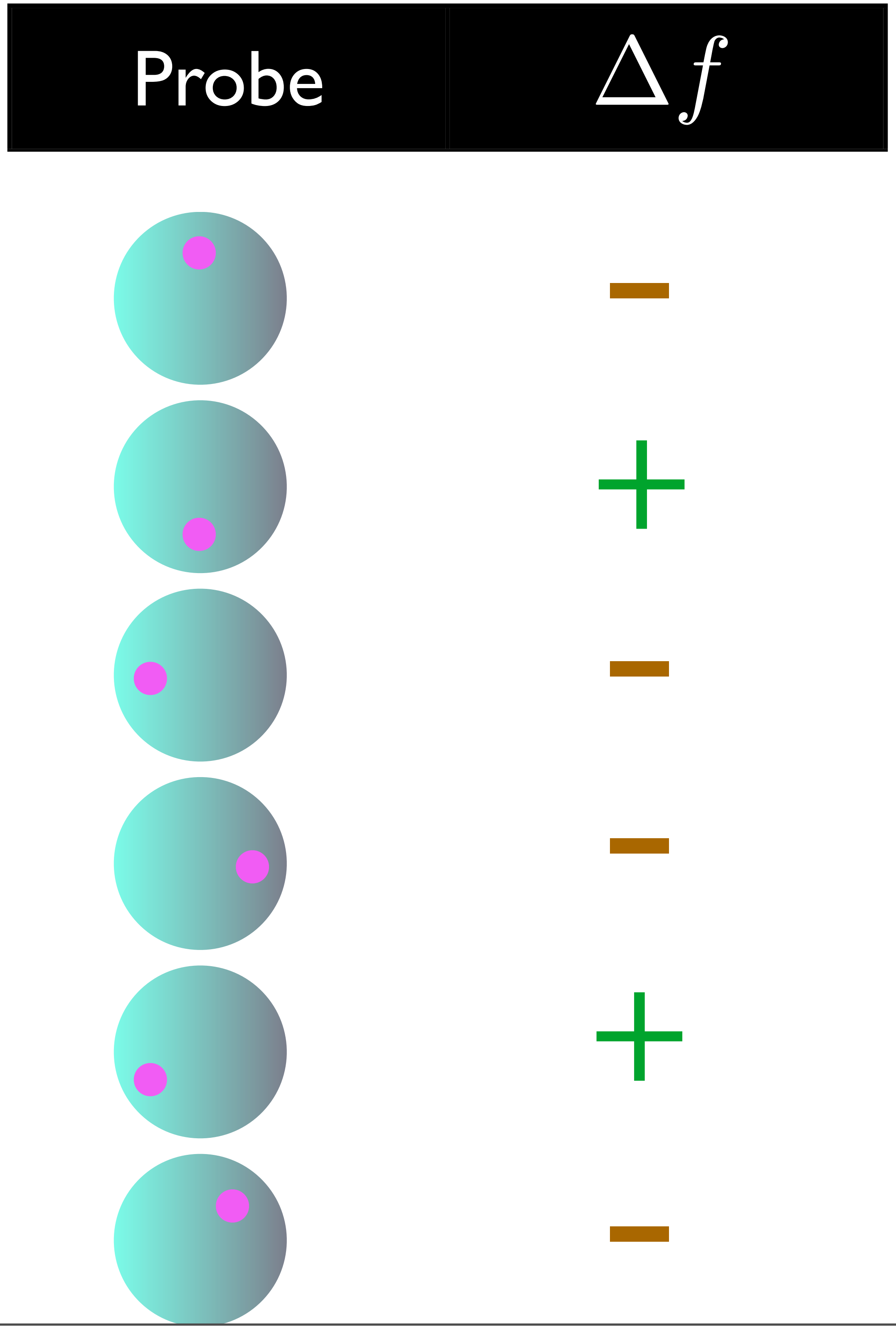
Curvature signature

Probe	Δf
	−

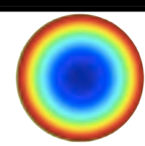
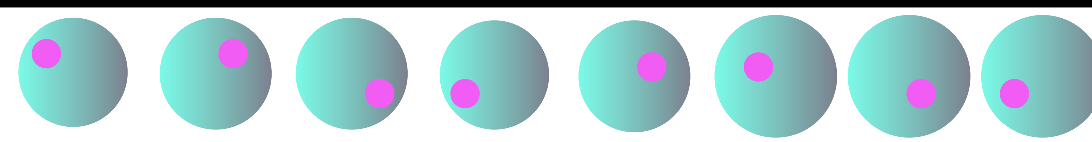
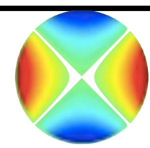
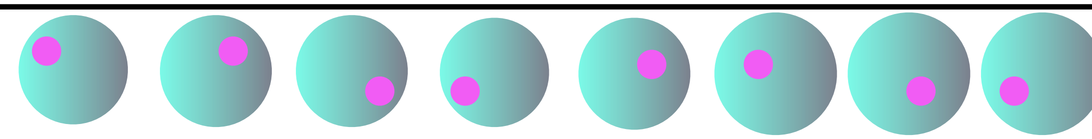
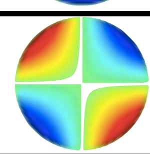
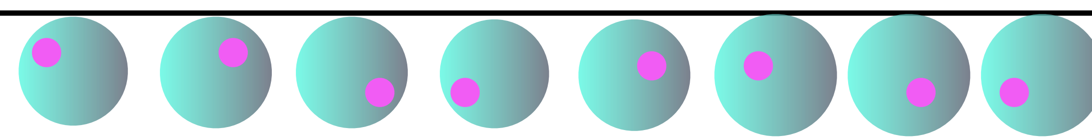
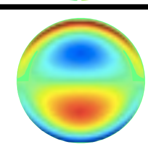
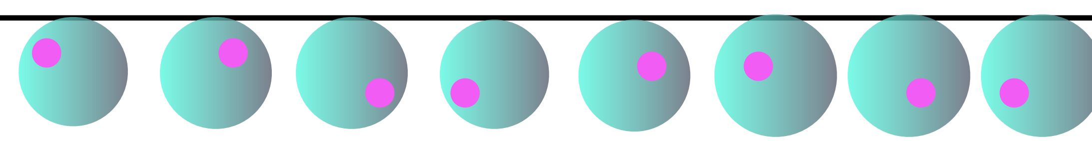
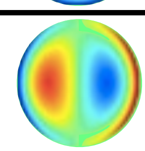
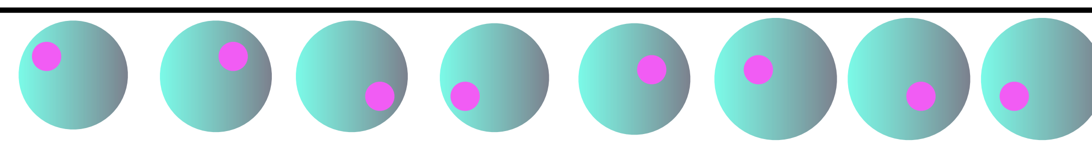
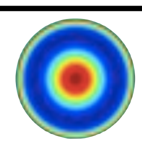
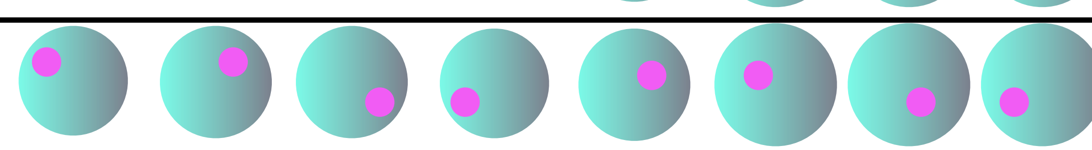
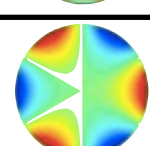
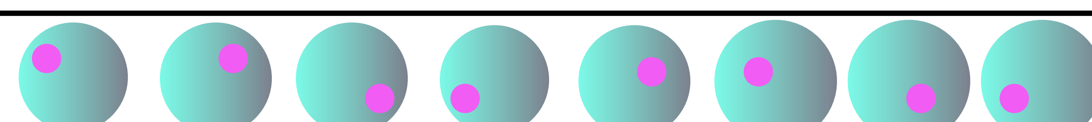
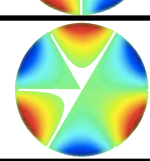
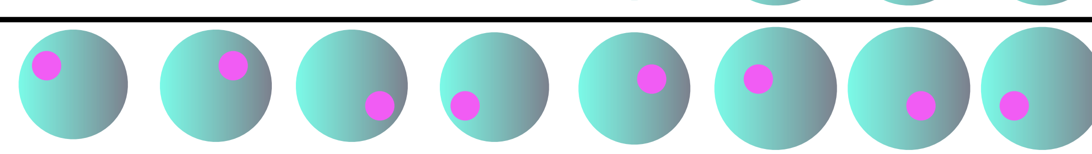
Z6: Coma



Curvature signature

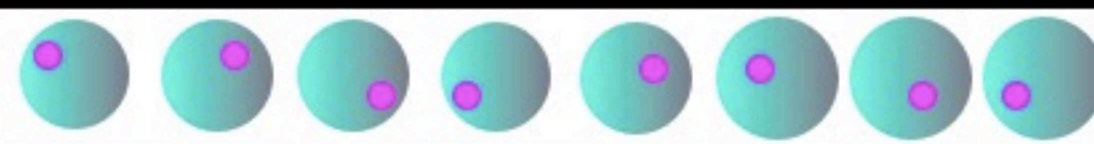
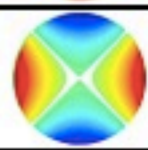
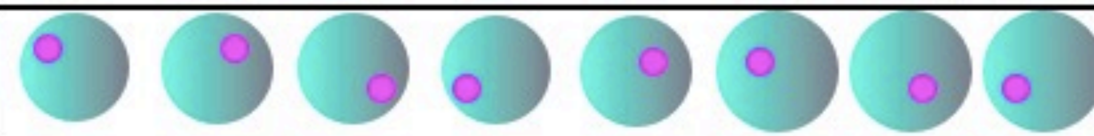
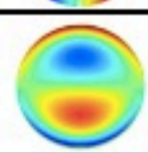
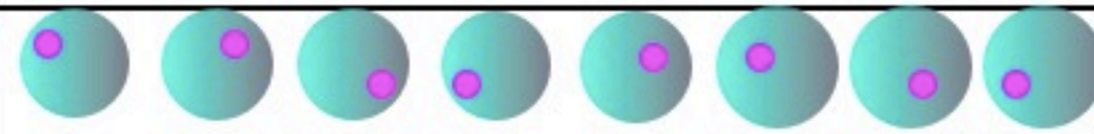
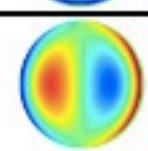
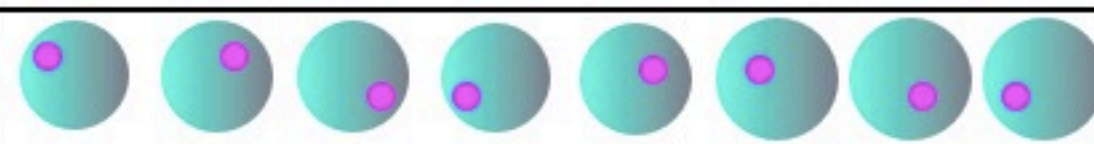
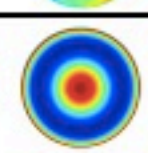
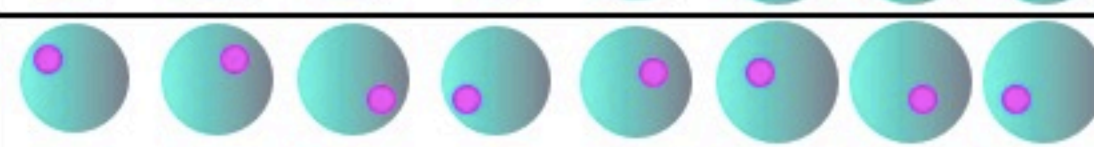
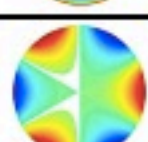
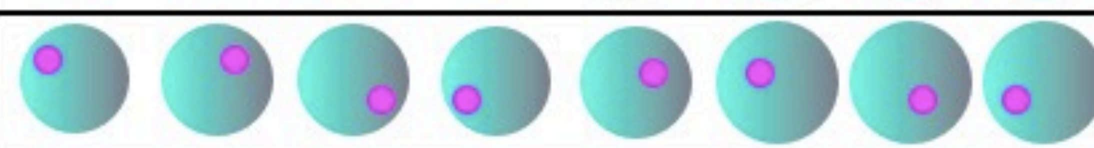
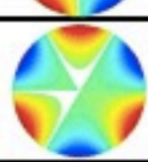
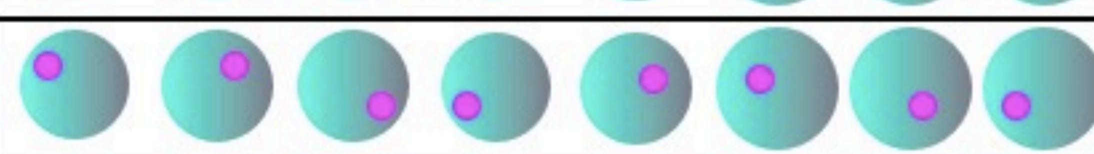


Curvature signatures of Zernike polynomials

N	Aberration		Probe	Δf
3	Focus			[+,-,+, -, -, +]
4	Stig			[-,-,+, -, -, +]
5	Stig			[-,-,+, +, -, +]
6	Coma			[+,-,+, -, +, +]
7	Coma			[+,+,+, -, -, +]
8	Spherical			[-,+,+, +, -, +]
9	Trifoil			[+,-,-, -, -, +]
10	Trifoil			[+,-,-, +, +, +]

Store for later use...

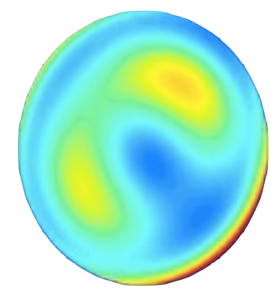
Curvature library

N	Aberration		Probe	Δf
3	Focus			[+,-,+, -, -, +]
4	Stig			[-,-,+, -, -, +]
5	Stig			[-,-,+, +, -, +]
6	Coma			[+,-,+, -, +, +]
7	Coma			[+,+,+, -, -, +]
8	Spherical			[-,+,+, +, -, +]
9	Trifoil			[+,-,-, -, -, +]
10	Trifoil			[+,-,-, +, +, +]

Store for later use...

Curvature library · **Wavefront** = **Focus shifts**

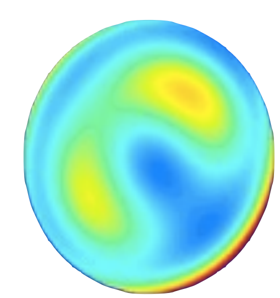
$\cdot$



$= \left[\ \Delta f\ \right]$

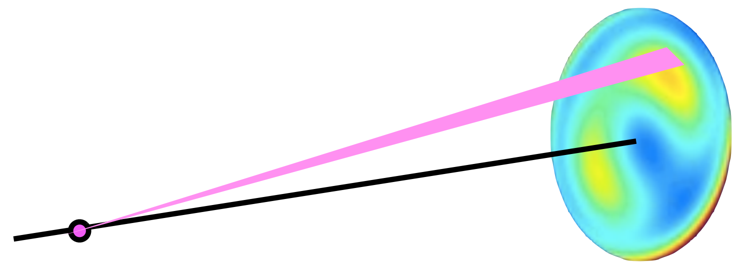
Curvature library † · **Focus shifts** $\approx$ **Wavefront**

$^{\dagger} \cdot \left[\ \Delta f\ \right] \approx$

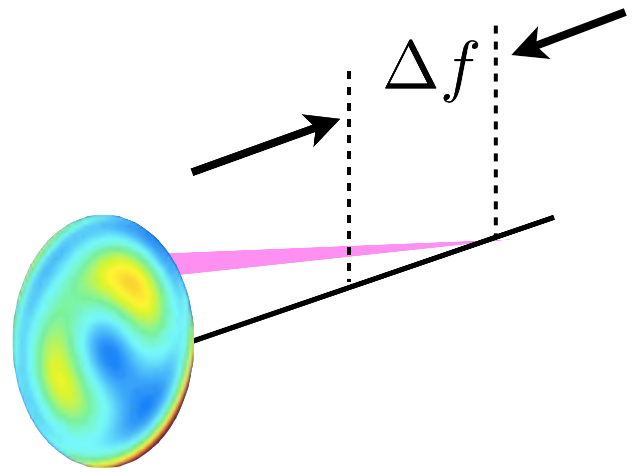


Wavefront sensor outline

Step 1: **Probe** localized regions of the pupil

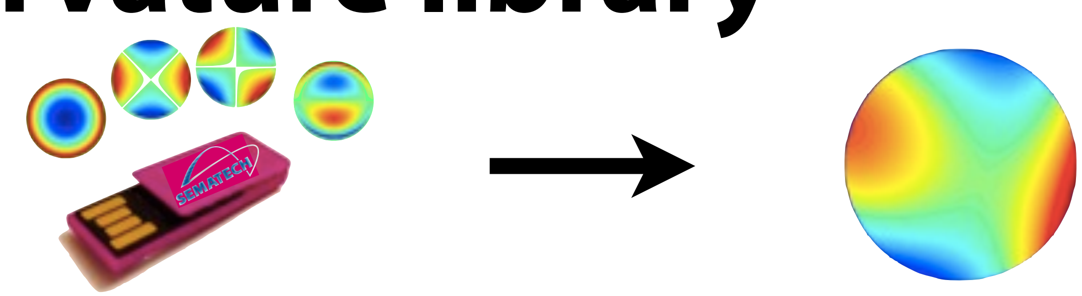


Step 2: Find the plane of **best focus** for each probe location

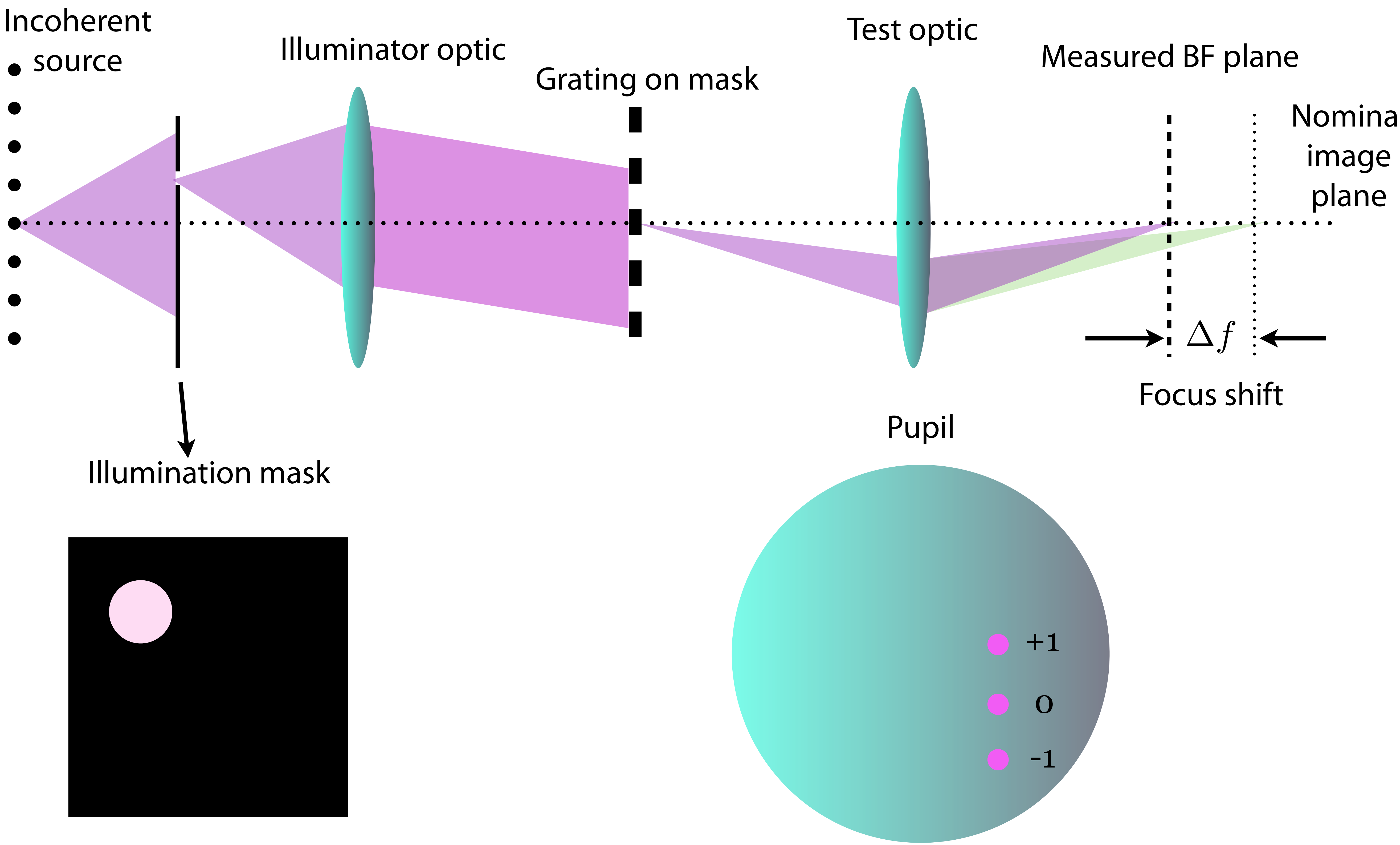


Step 3: Convert these focus shifts into an aberration map using **curvature library**

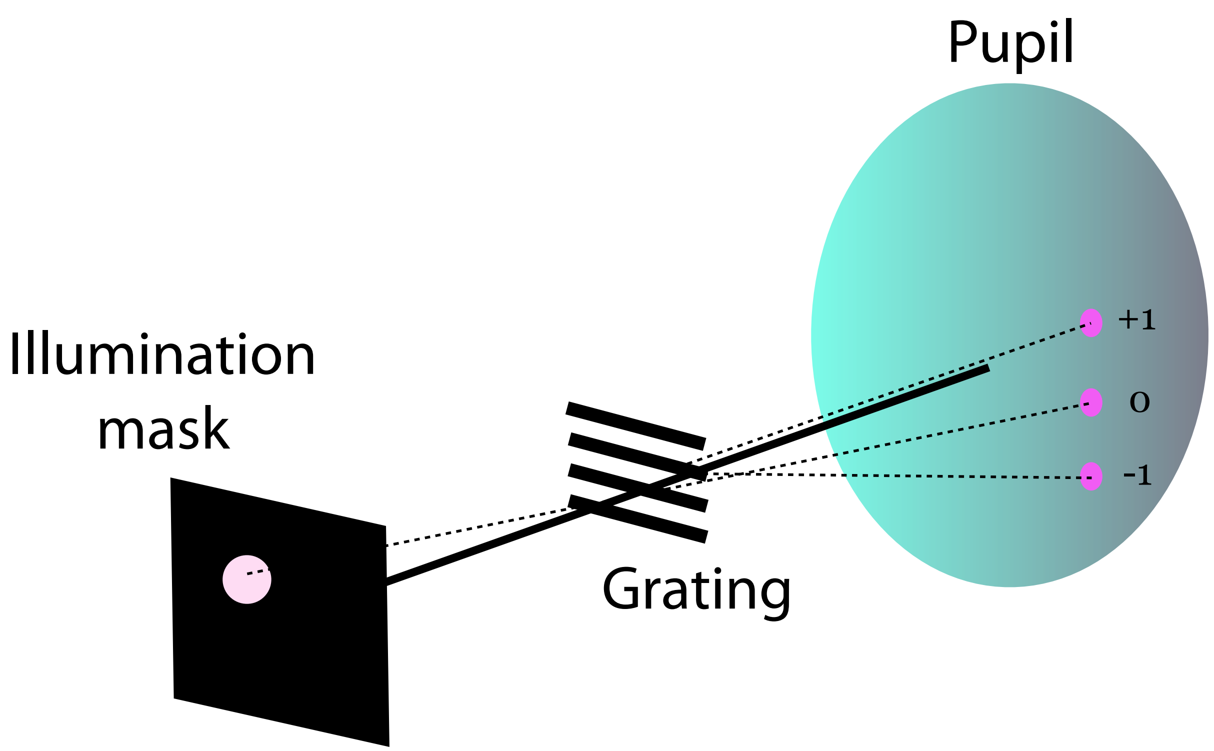
Δf →

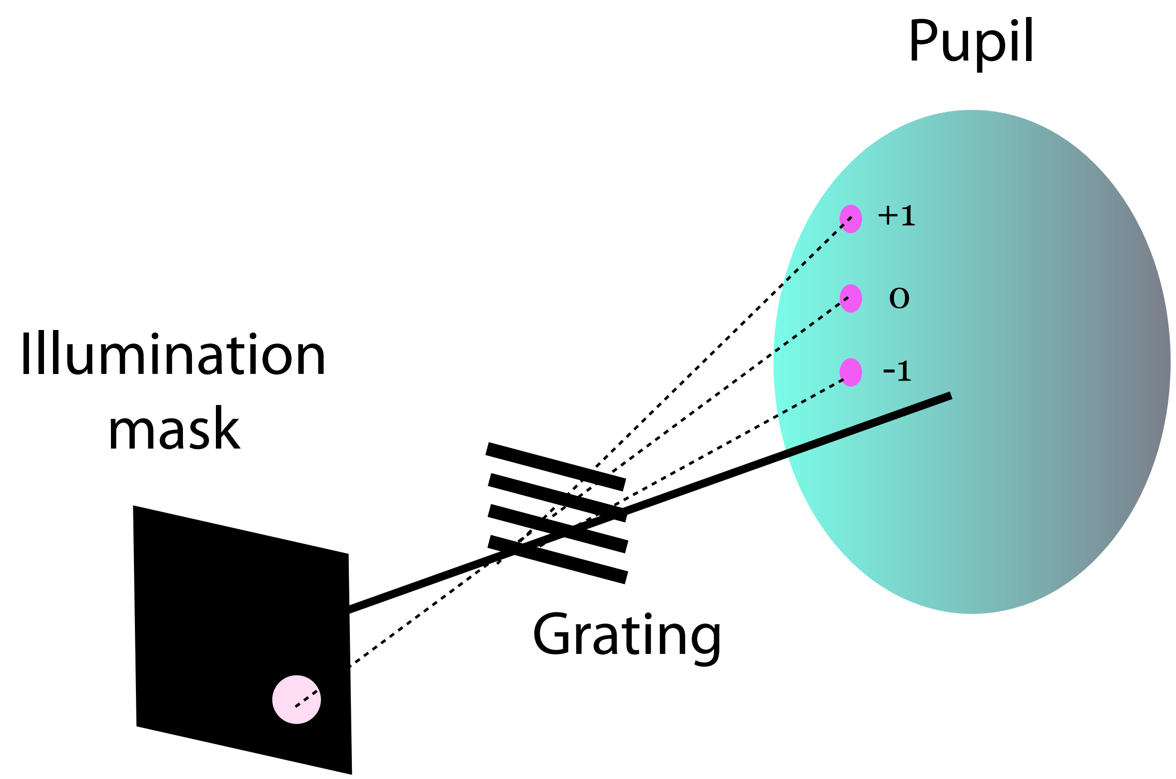


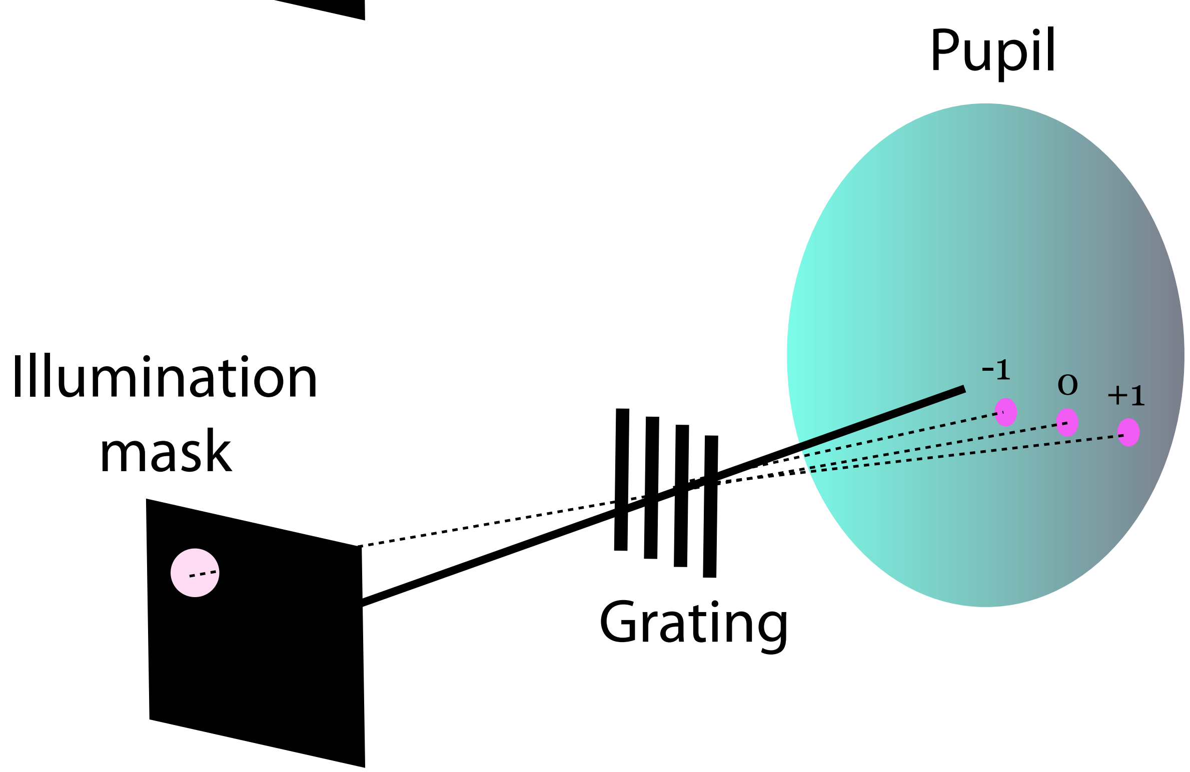
Schematic of illumination principle



Customized illumination to probe pupil

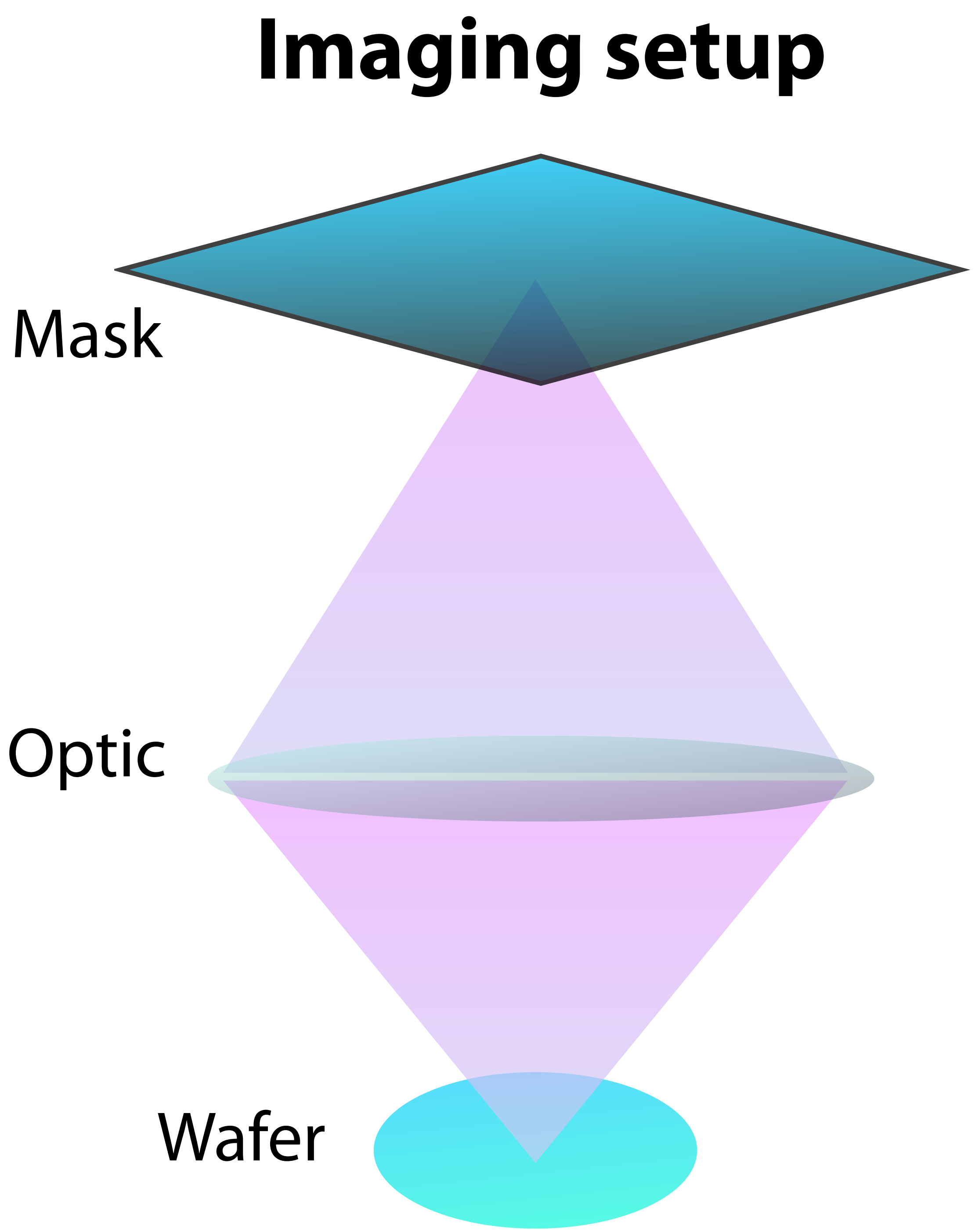


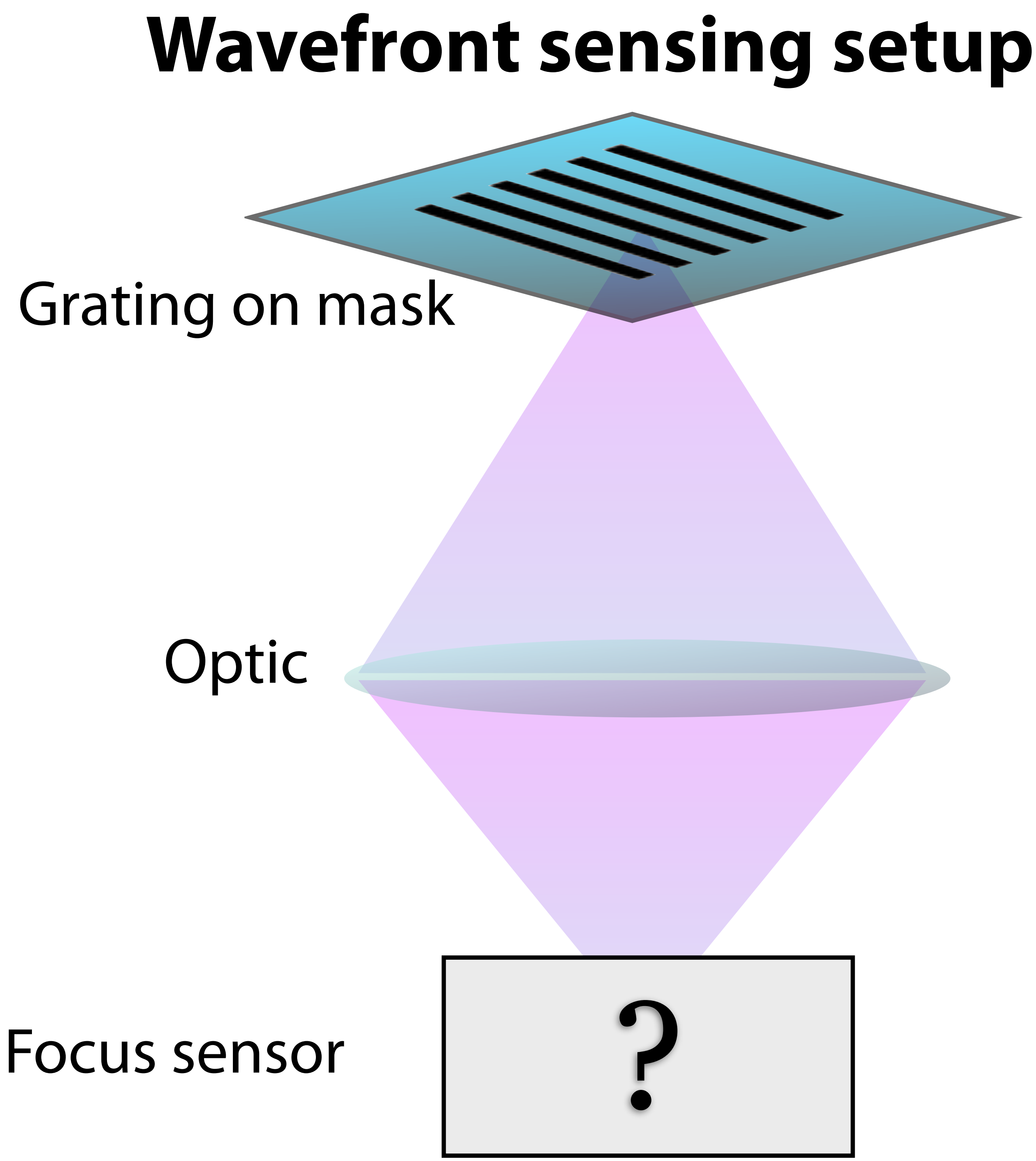




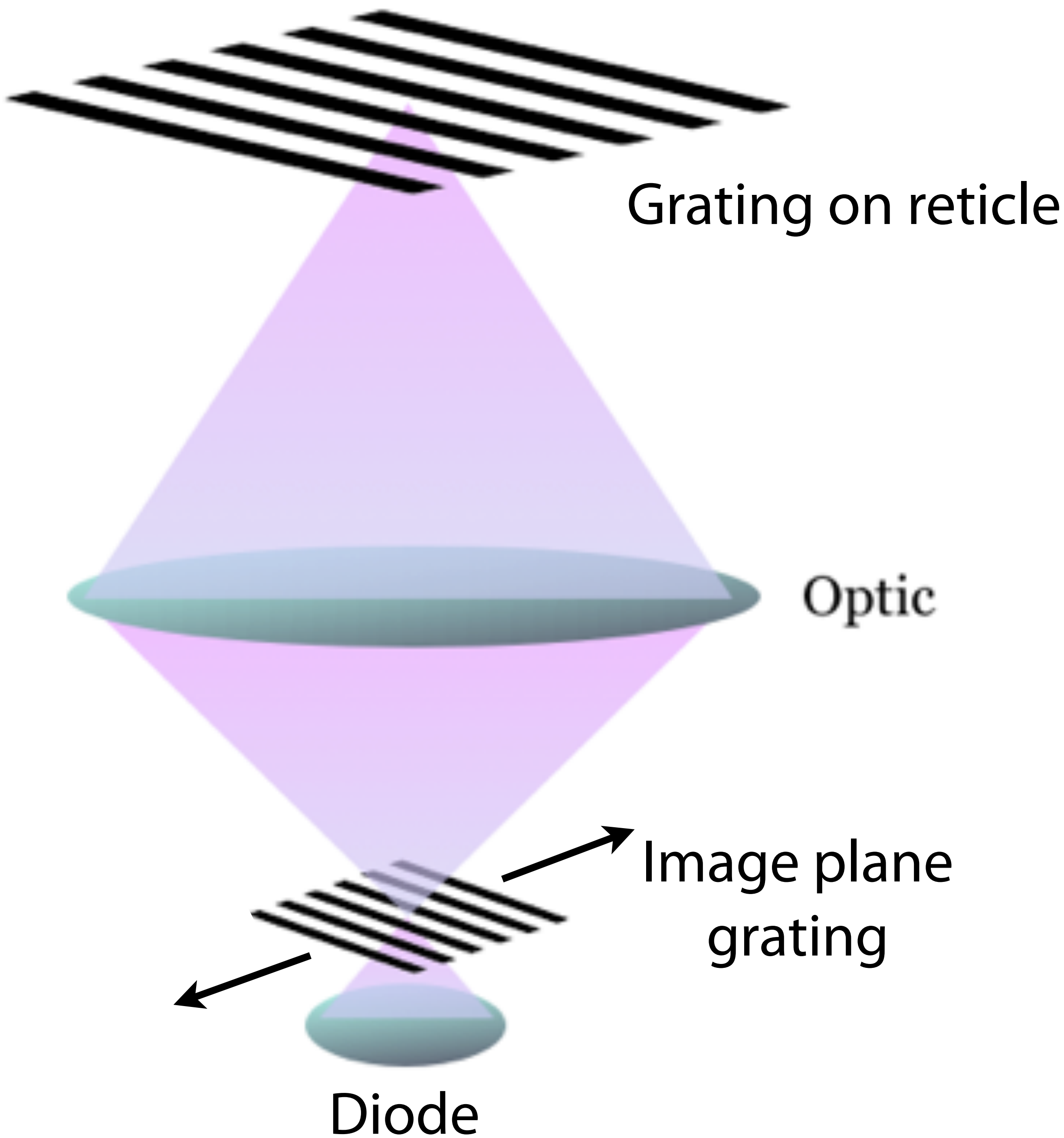
- Order separation determined by grating pitch
- Probe orientation determined by grating orientation
- Zero order location determined by illumination mask

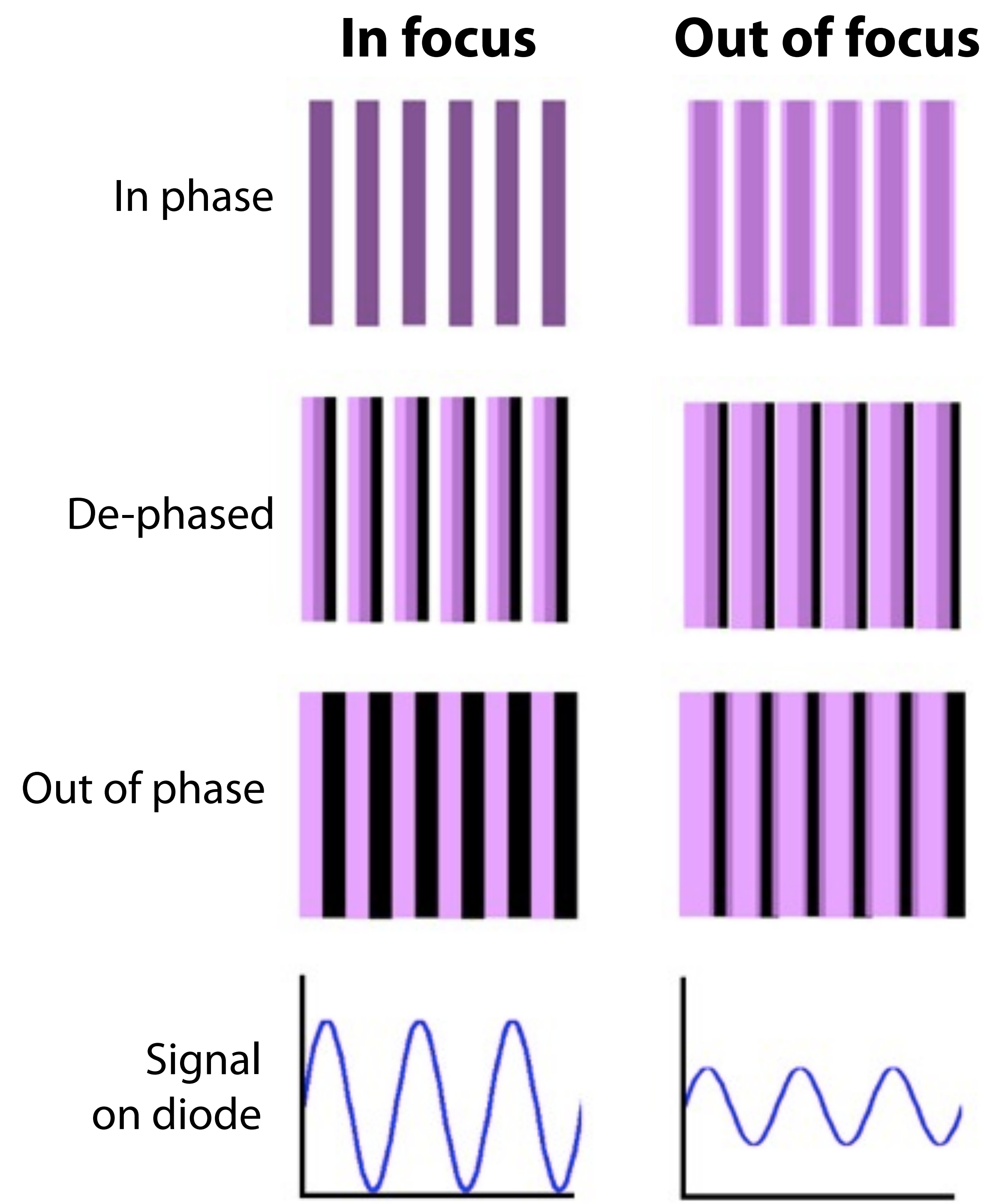
Swap wafer with focus sensor



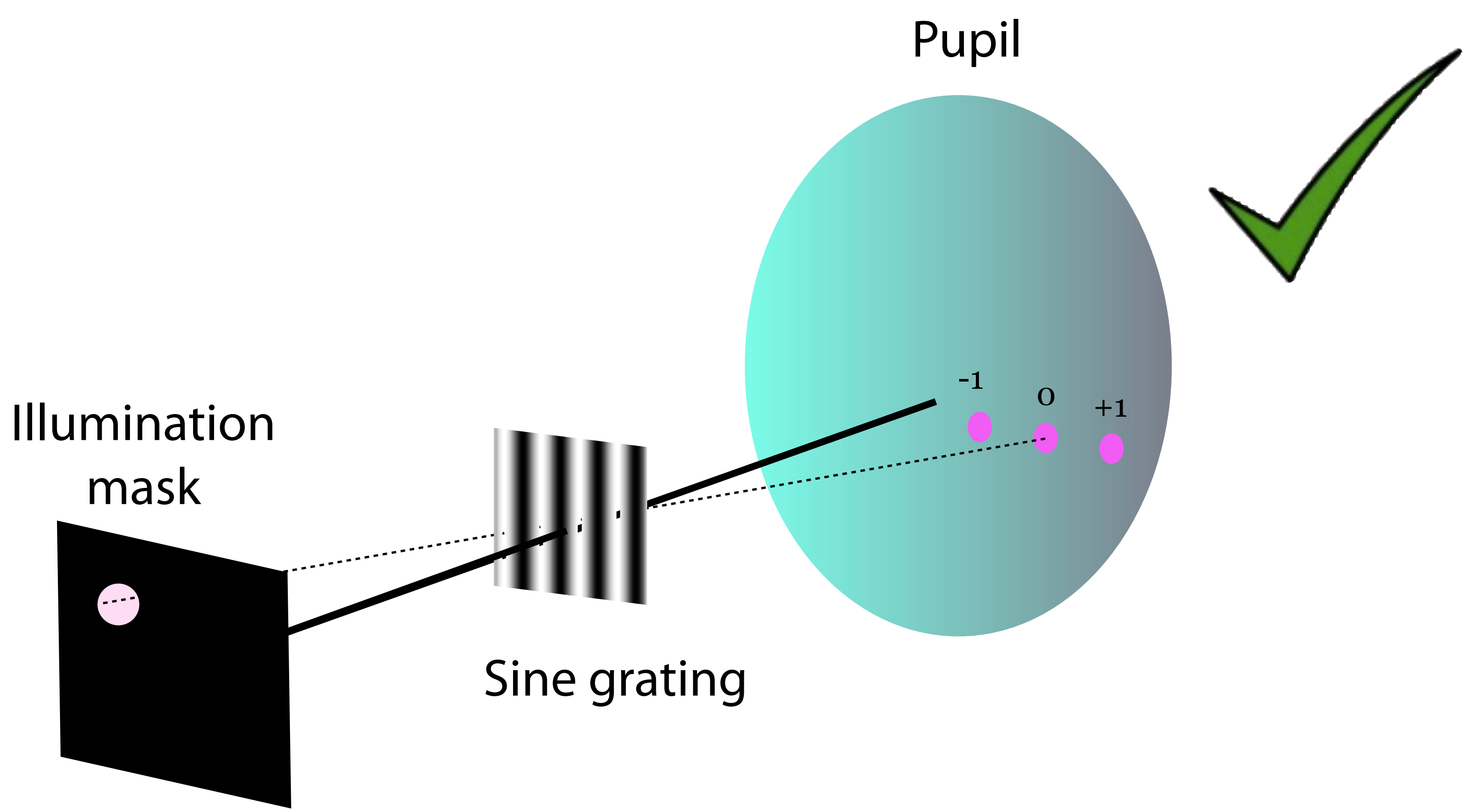


How to measure plane of best focus?

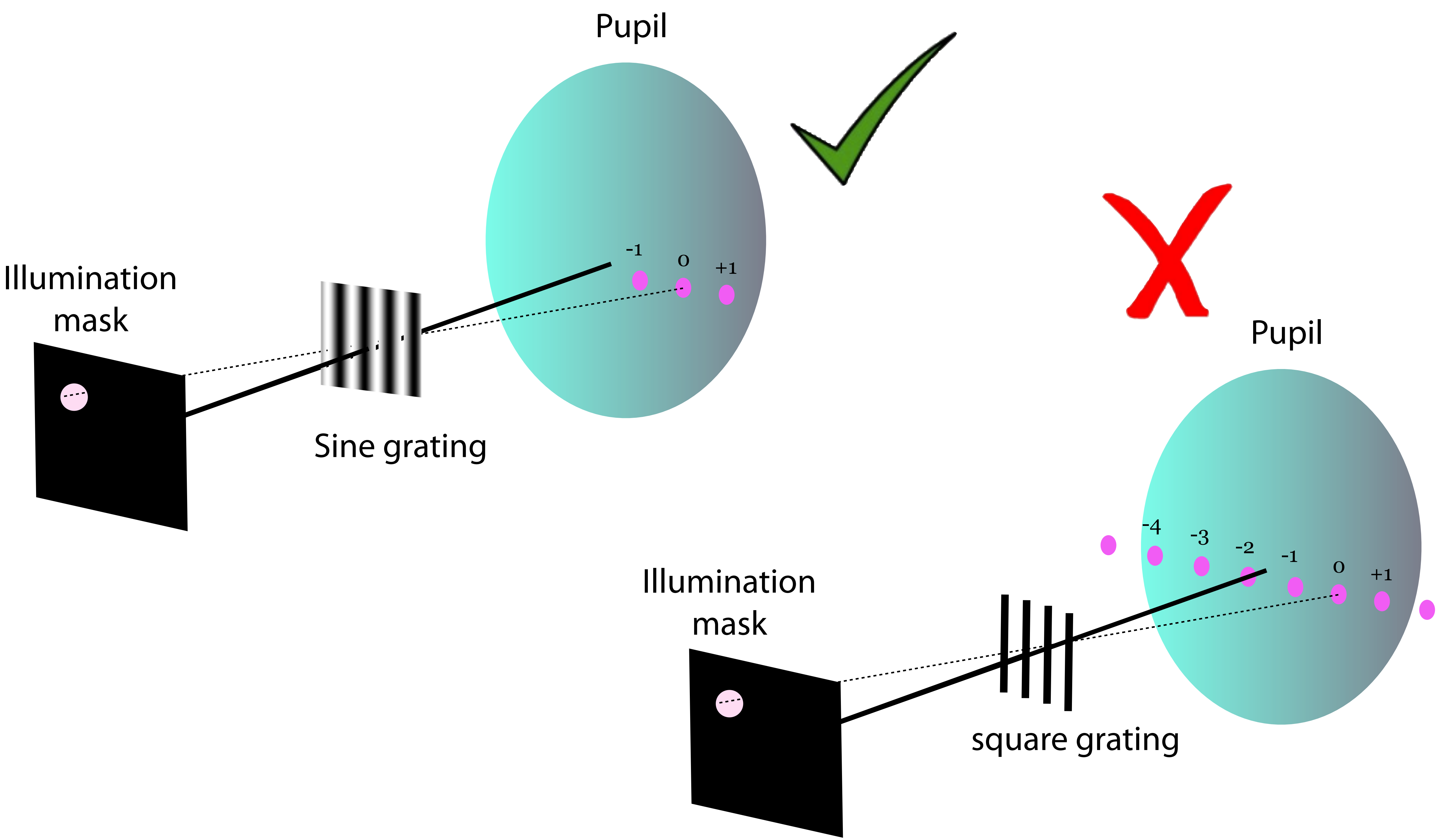




Binary gratings have many orders

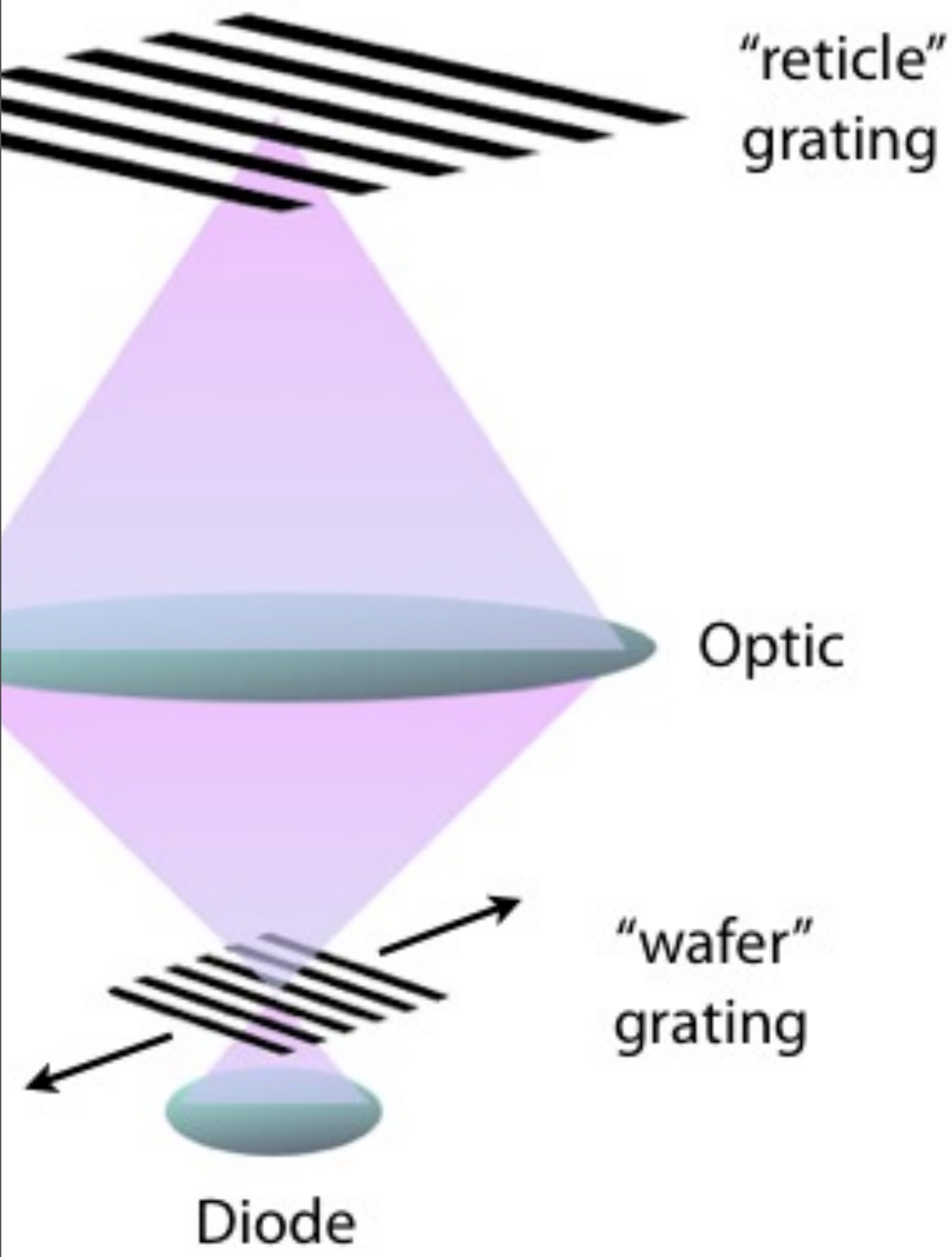


Binary gratings have many orders



Question: *Can we use a binary structure that mimics the properties of a sine grating?*

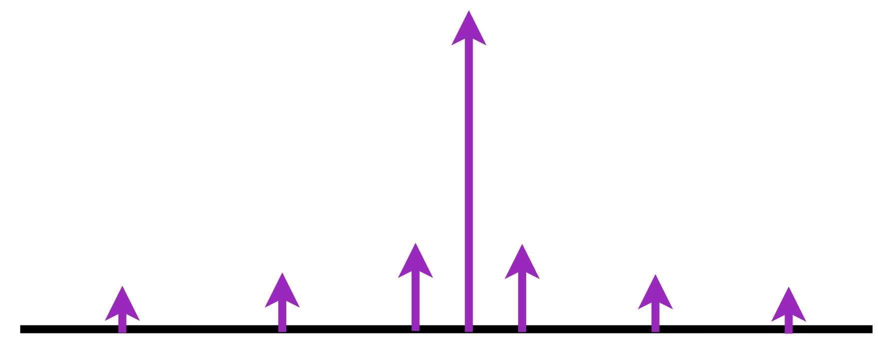
A trick in the Fourier domain...



$g(x)$

square

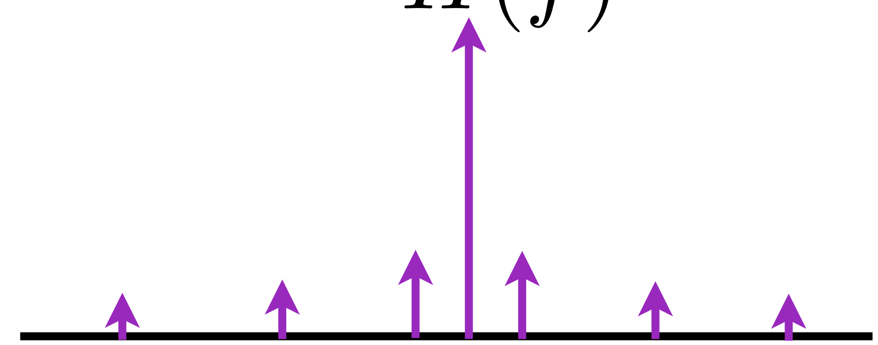
$G(f)$



$h(x)$

square

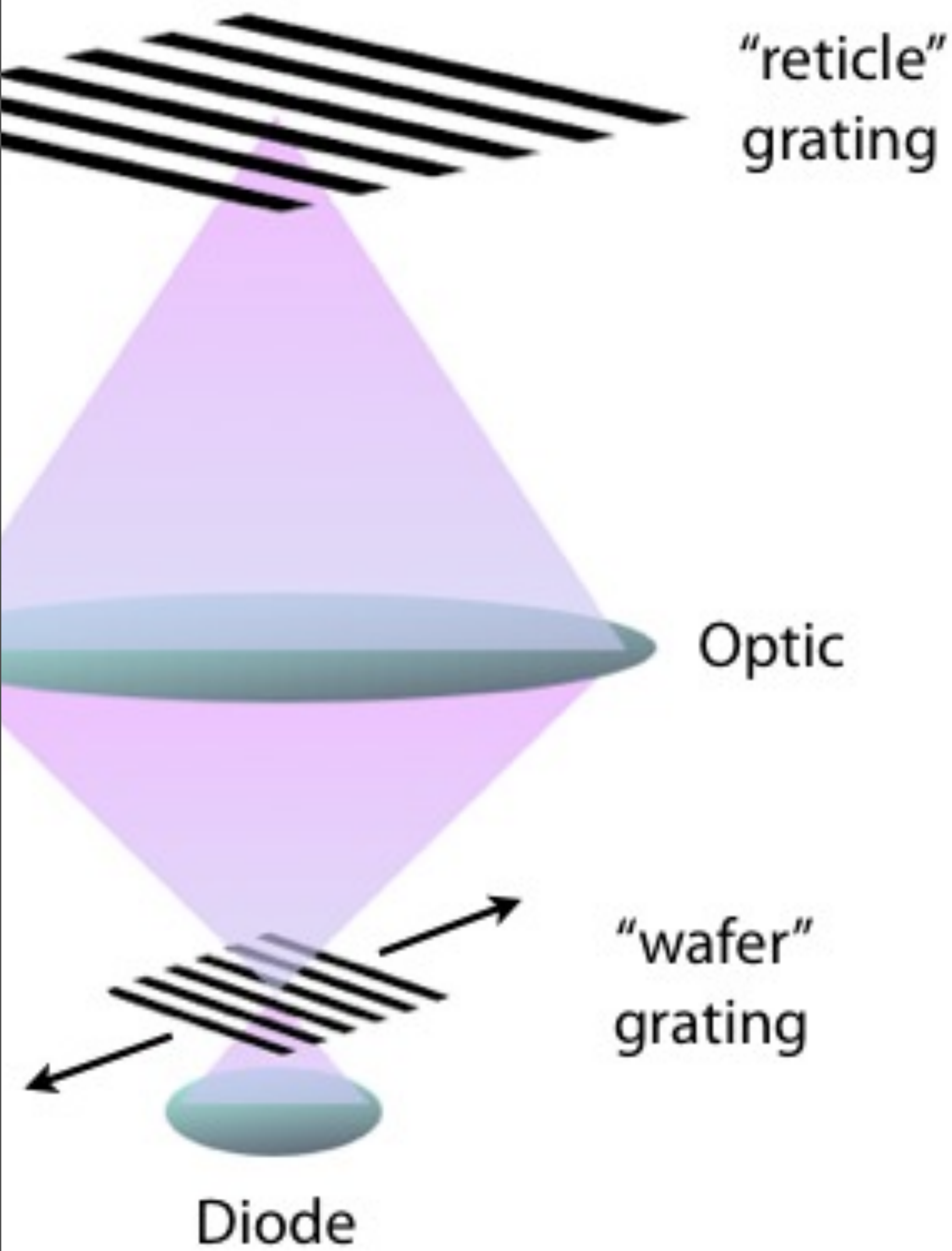
$H(f)$



$$i(x) = g * h$$

$$I(f) = G \cdot H$$

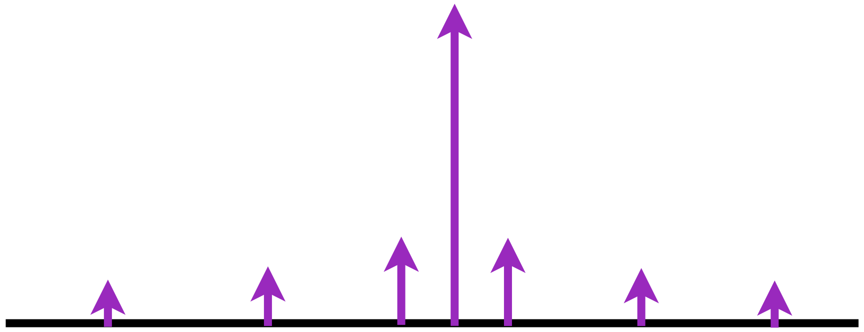
A trick in the Fourier domain...



$g(x)$

square

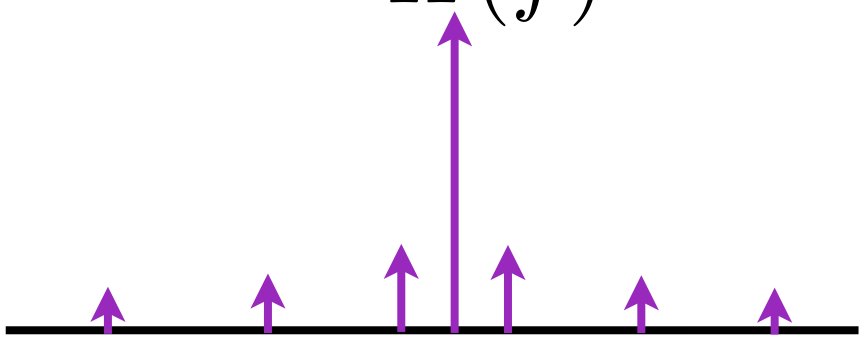
$G(f)$



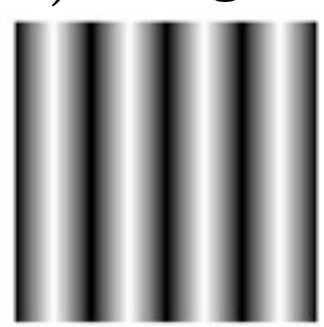
$h(x)$

square

$H(f)$

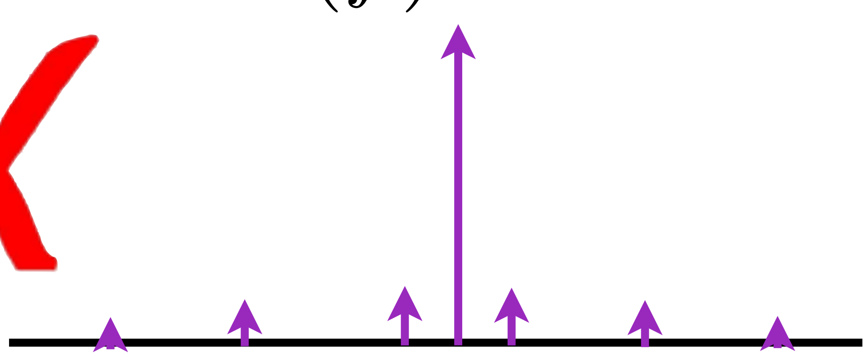


$i(x) = g * h$



triangular

$I(f) = G \cdot H$



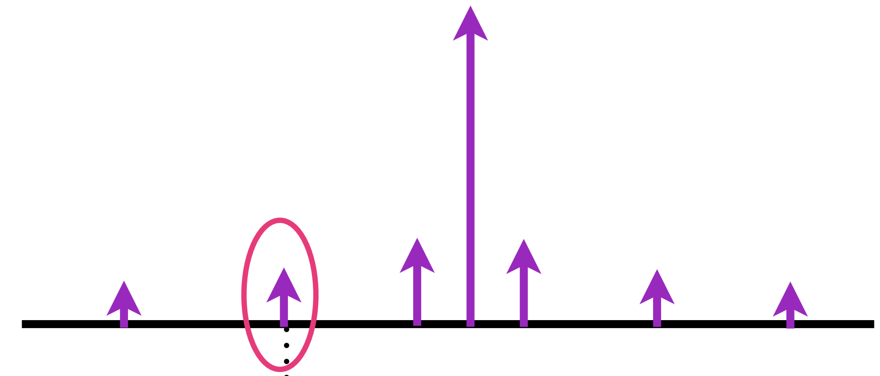
A trick in the Fourier domain...

Reticle grating

$g(x)$

square

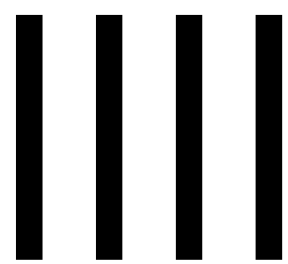
$G(f)$



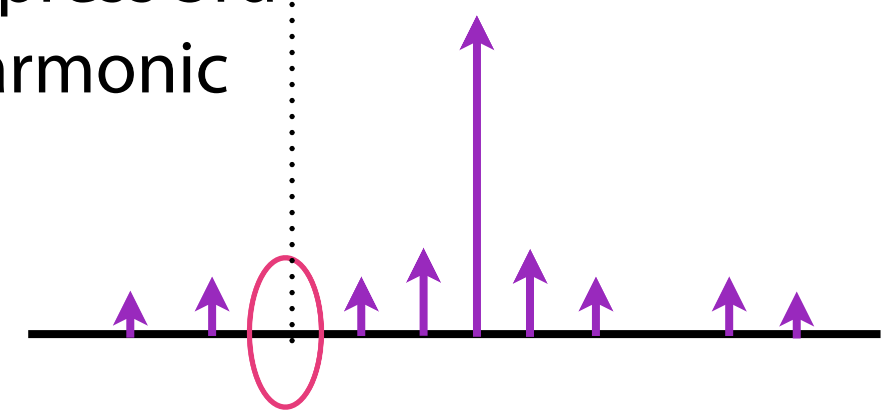
suppress 3rd harmonic

Wafer grating

$h(x)$



33 % DC square



$$i(x) = g * h$$

$$I(f) = G \cdot H$$

A trick in the Fourier domain...

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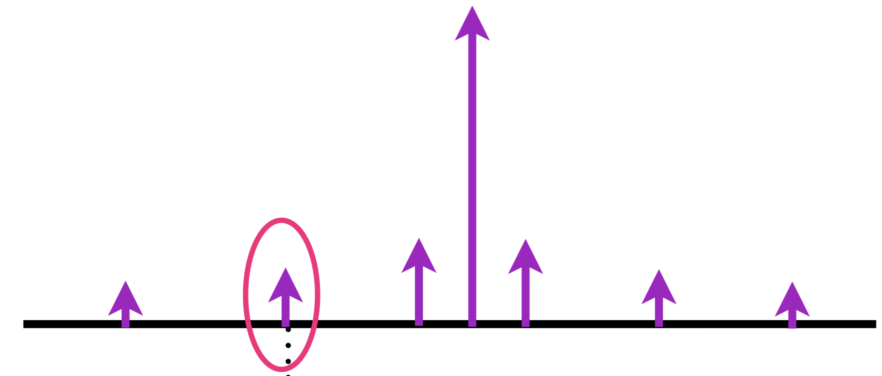
Reticle grating

$g(x)$

square

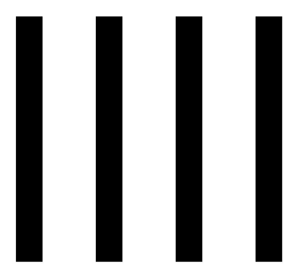
$G(f)$



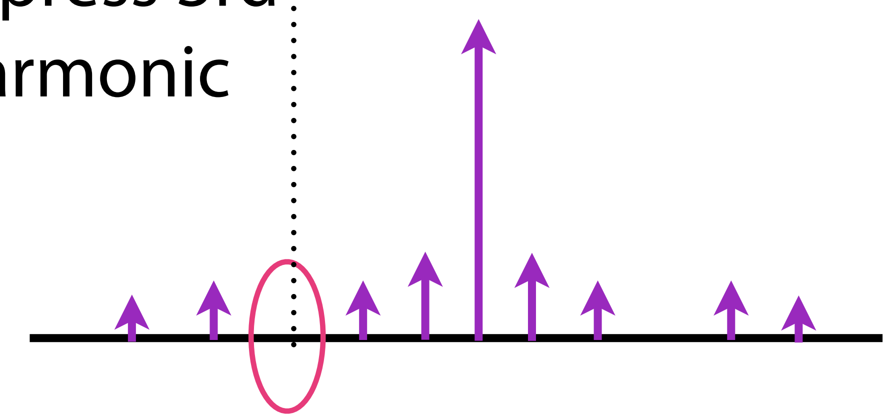
suppress 3rd harmonic

Wafer grating

$h(x)$

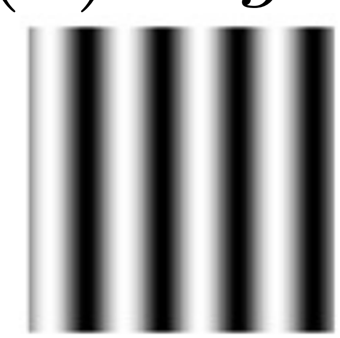


33 % DC square



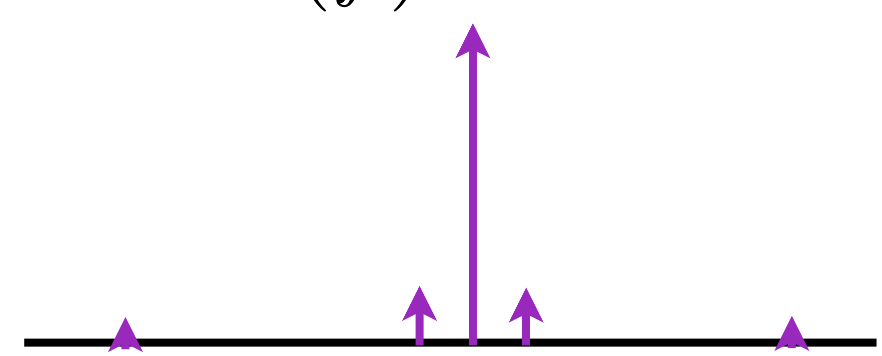
Signal at diode

$i(x) = g * h$



approximate sine

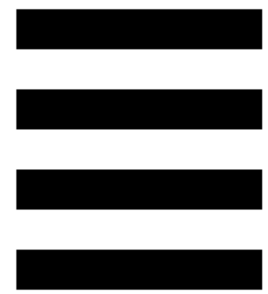
$I(f) = G \cdot H$



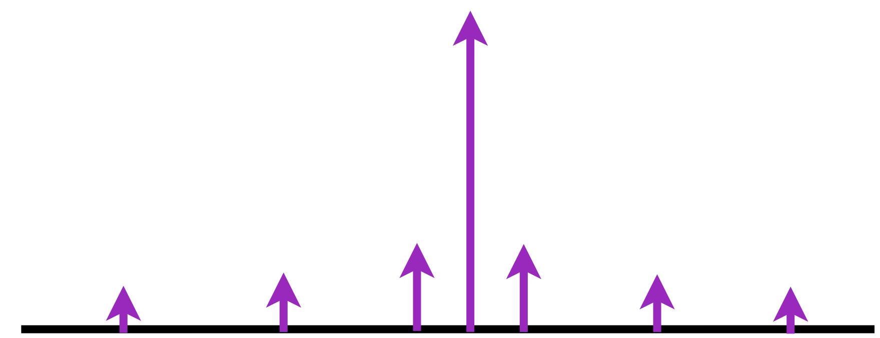
A trick in the Fourier domain...

Reticle grating

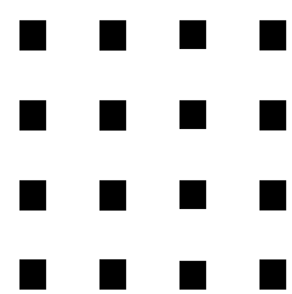
or



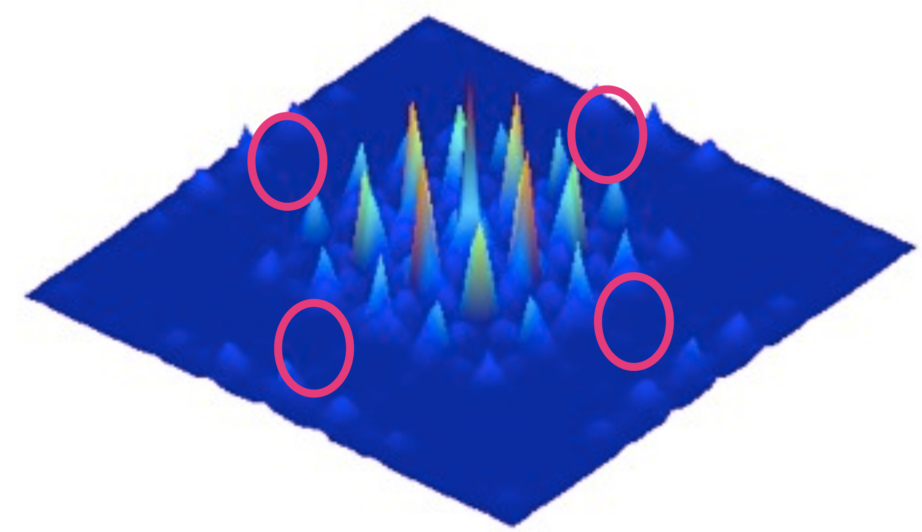
square



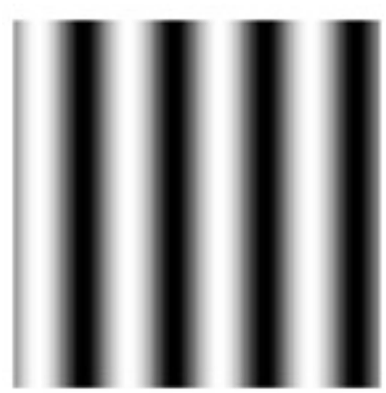
Wafer grating



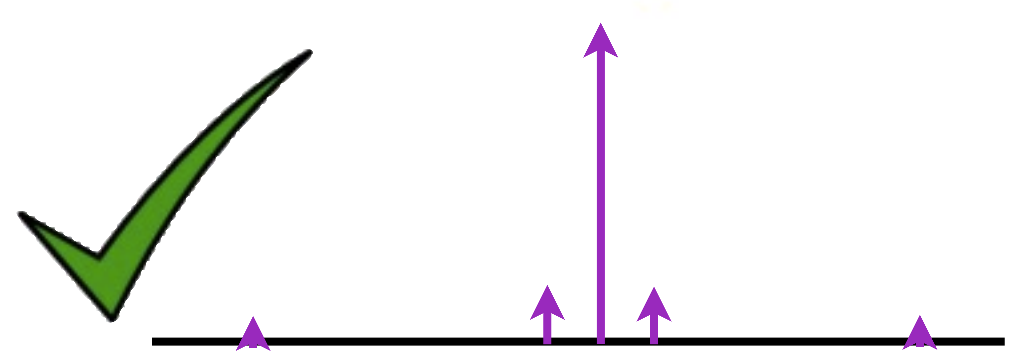
33 % DC
2D square



Signal at diode

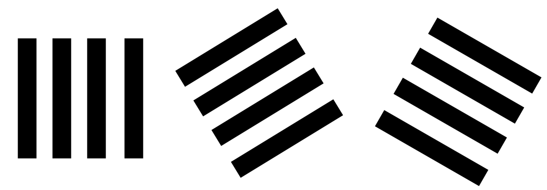


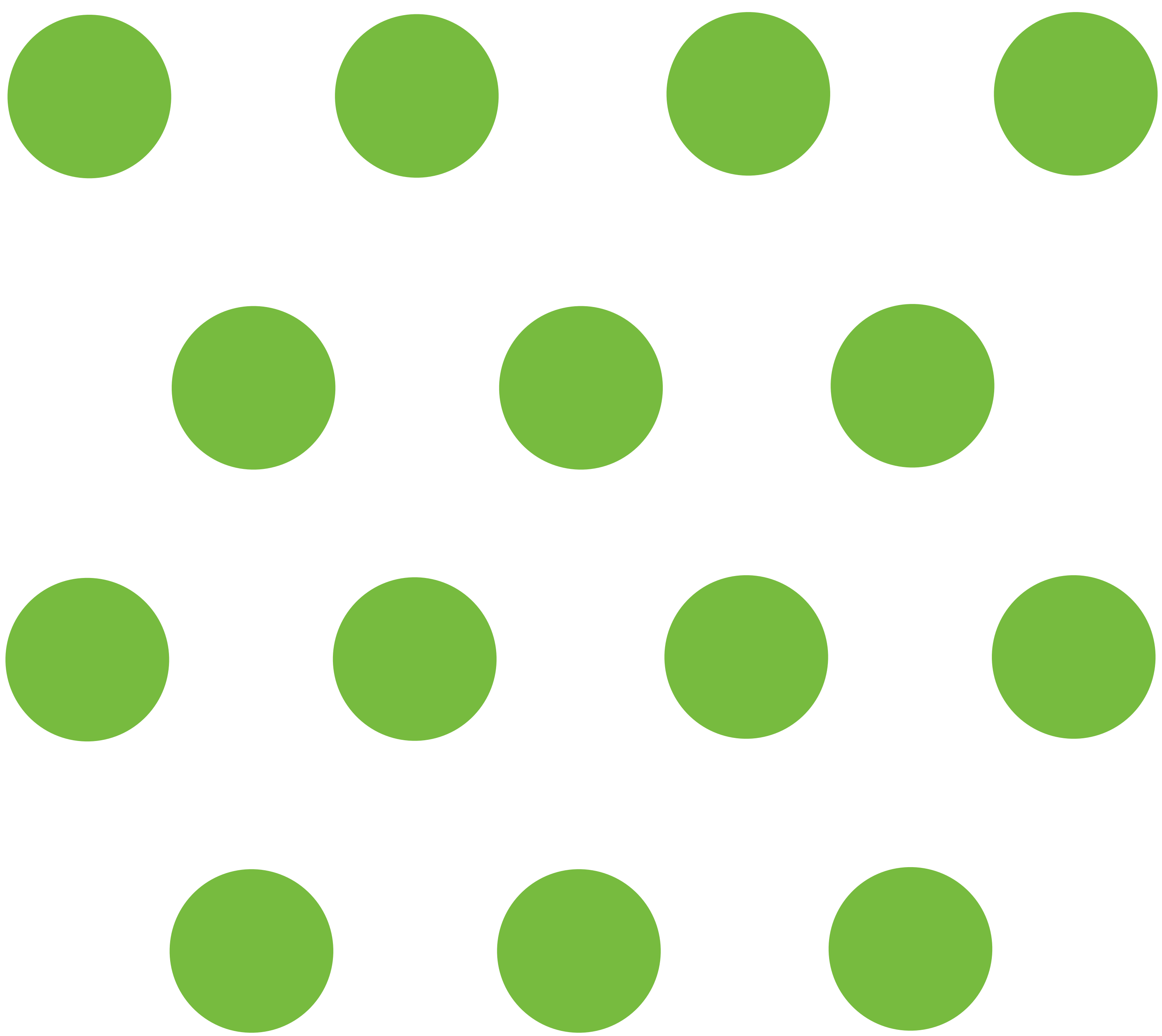
Approximate sine



Pinhole arrays (6-fold symmetry)

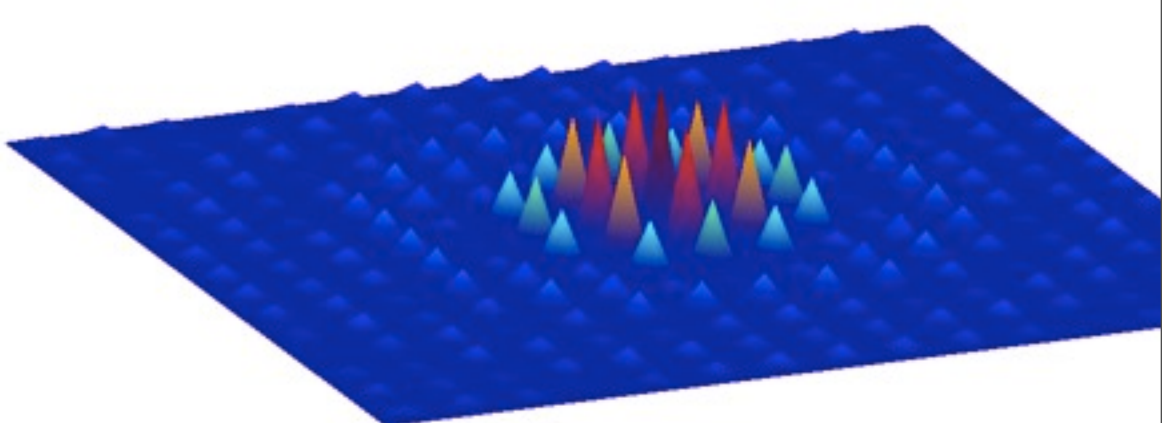
Supports 3 grating orientations:





Pinhole shape specifies envelope

Suppressed 3rd harmonic with first Bessel function zero

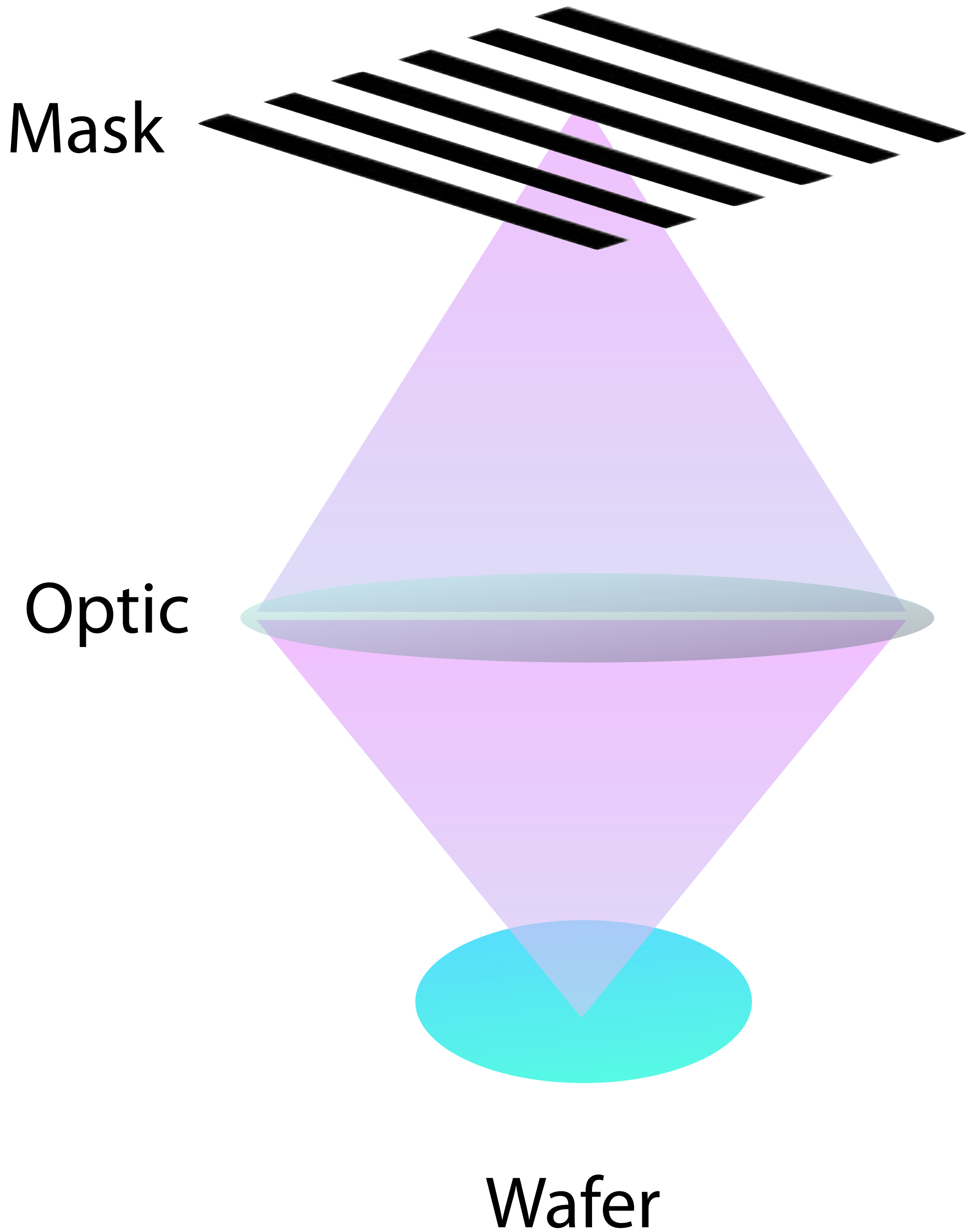


$$\frac{\mathrm{CD}}{\mathrm{pitch}} = 0.404$$

Wafer and focus sensor are easily swapped

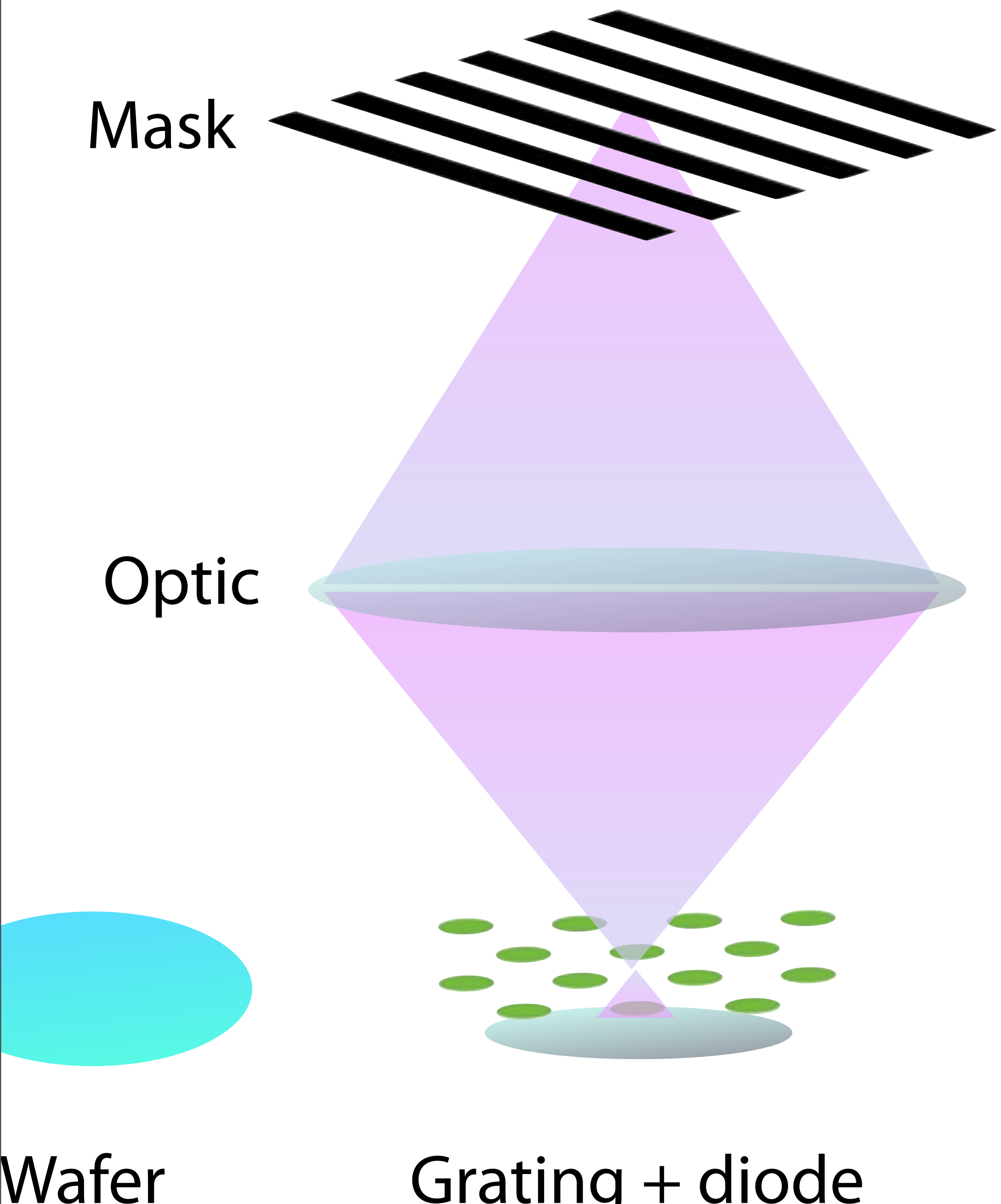
THE CENTER FOR X-RAY OPTICS

Imaging setup

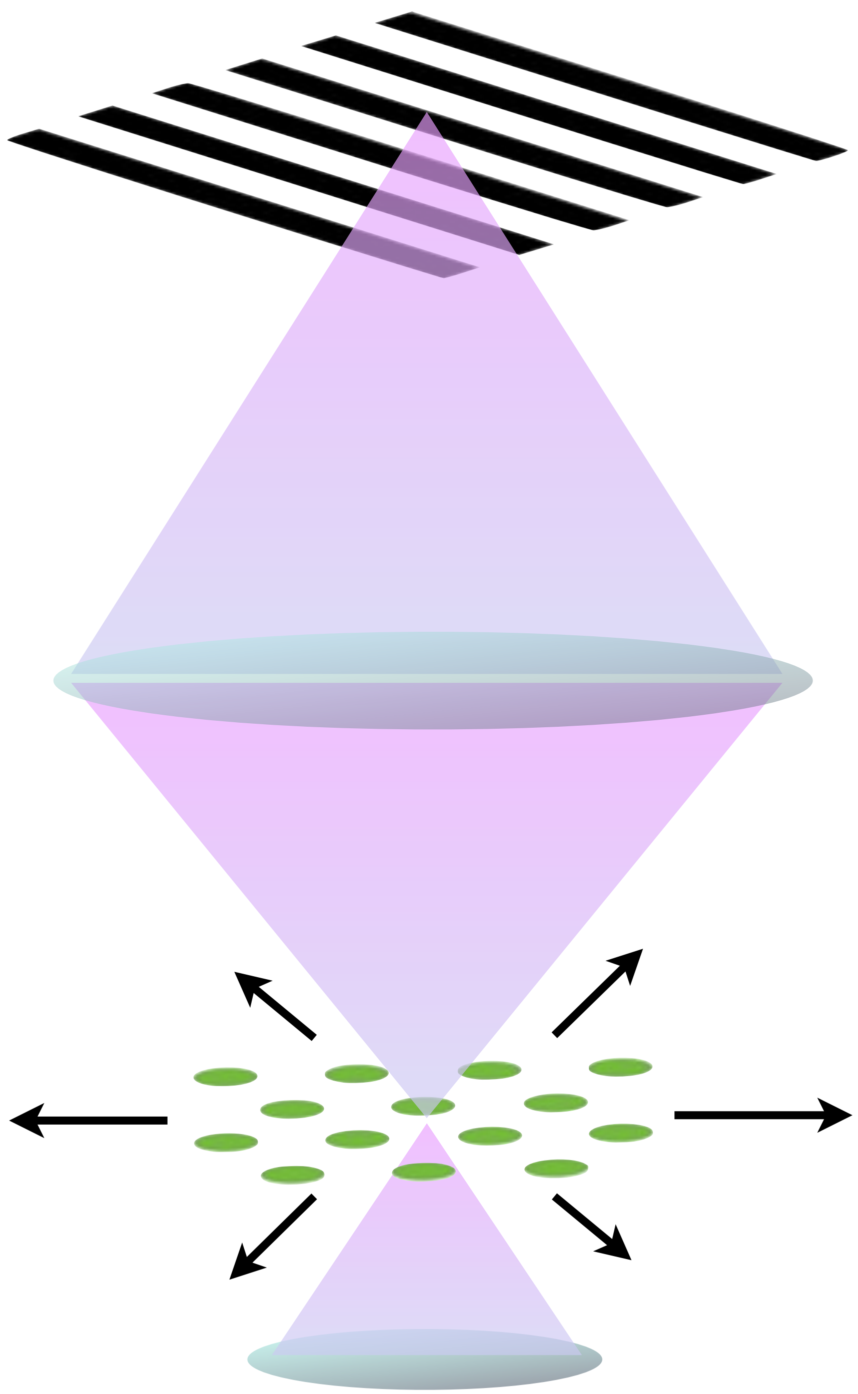


Simple yet versatile technique

Imaging setup



Simulation of wavefront reconstruction



- Use randomly selected wavefront from Zernike polynomials 1-24
- 16 pupil probe points, 3 grating orientations
- 21 steps through focus
- Various values of grating pitch and shot noise were considered

Simulation results

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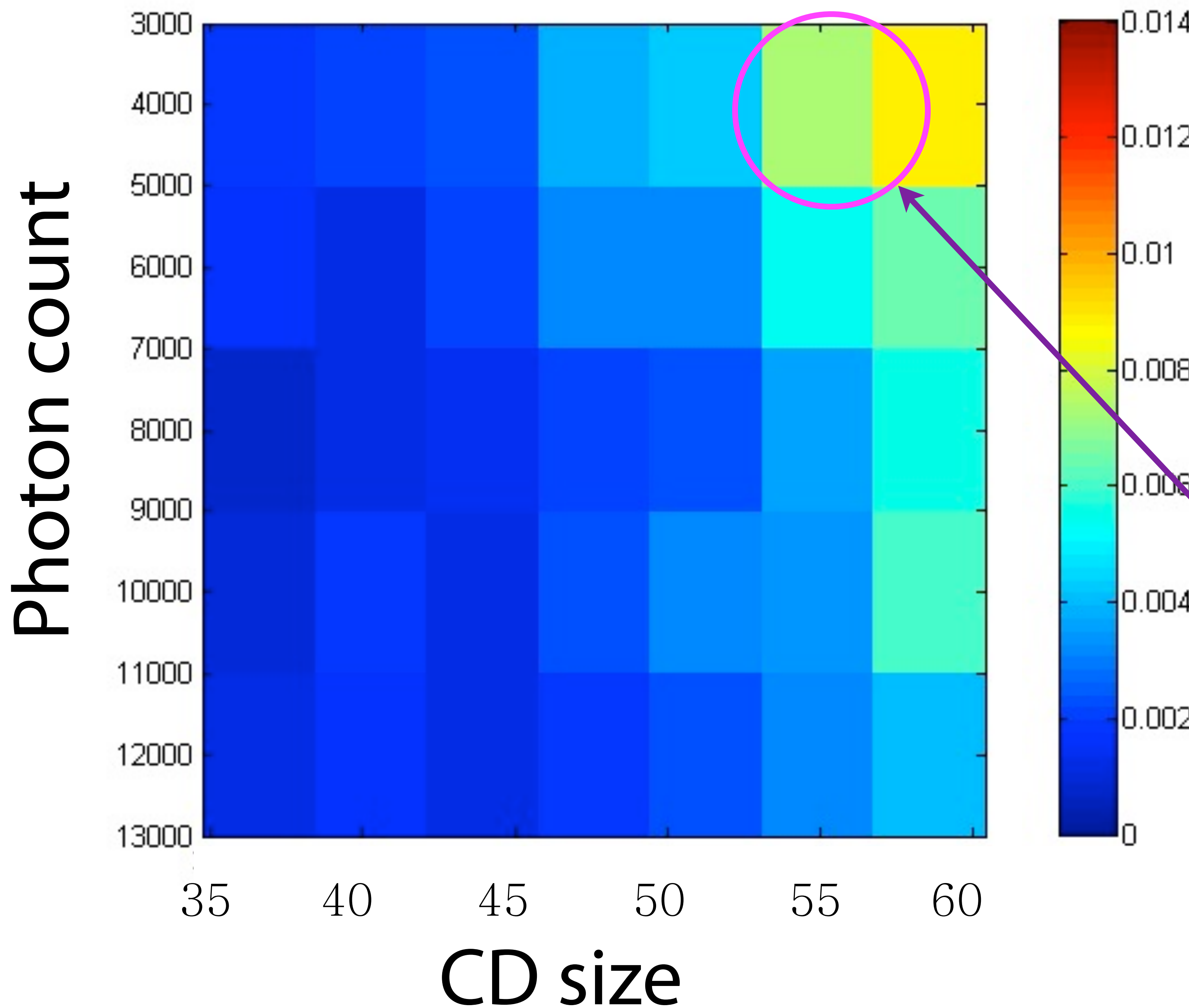
Wavefront reconstruction error



* Each data point is the average of 20 independent trials

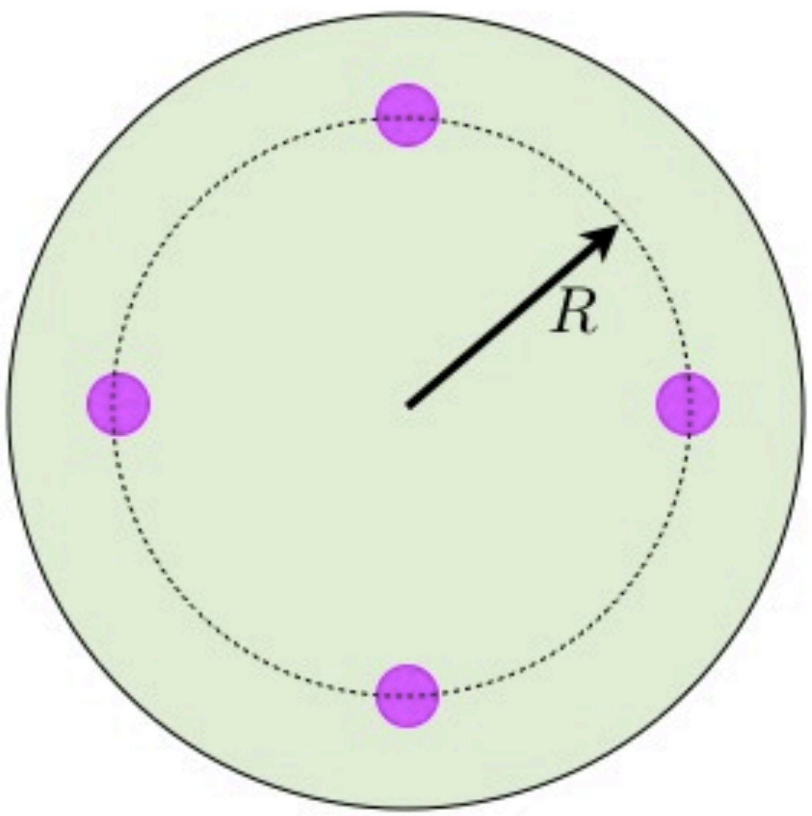
$\lambda_{EUV}/100$ accuracy with 3500 photons/ measurement

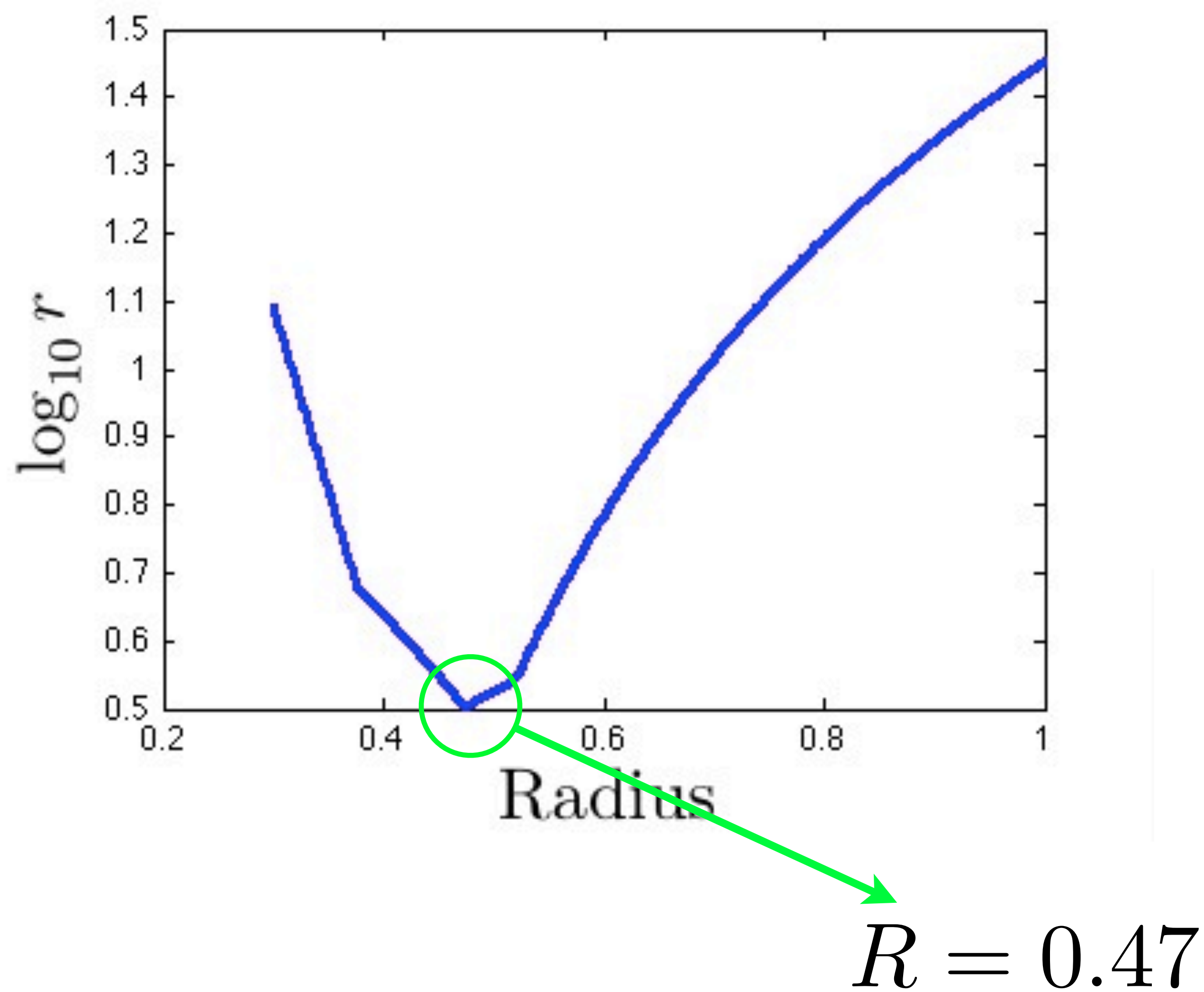
Optimizing probe configuration

Optimizing probe configuration

The condition number can be used as a metric for optimizing probe configuration

4 probe points:

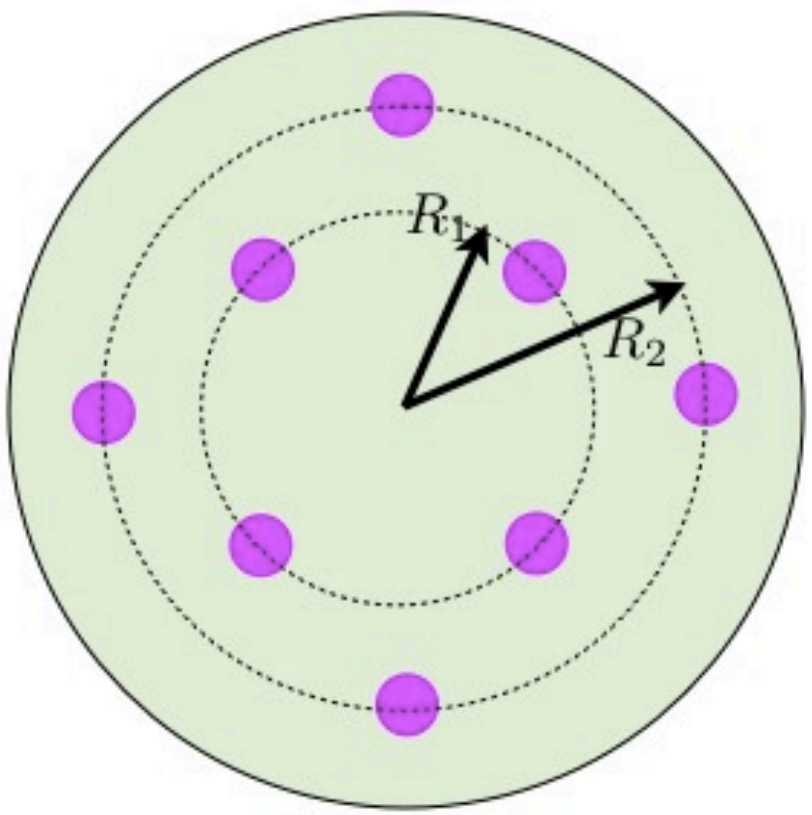


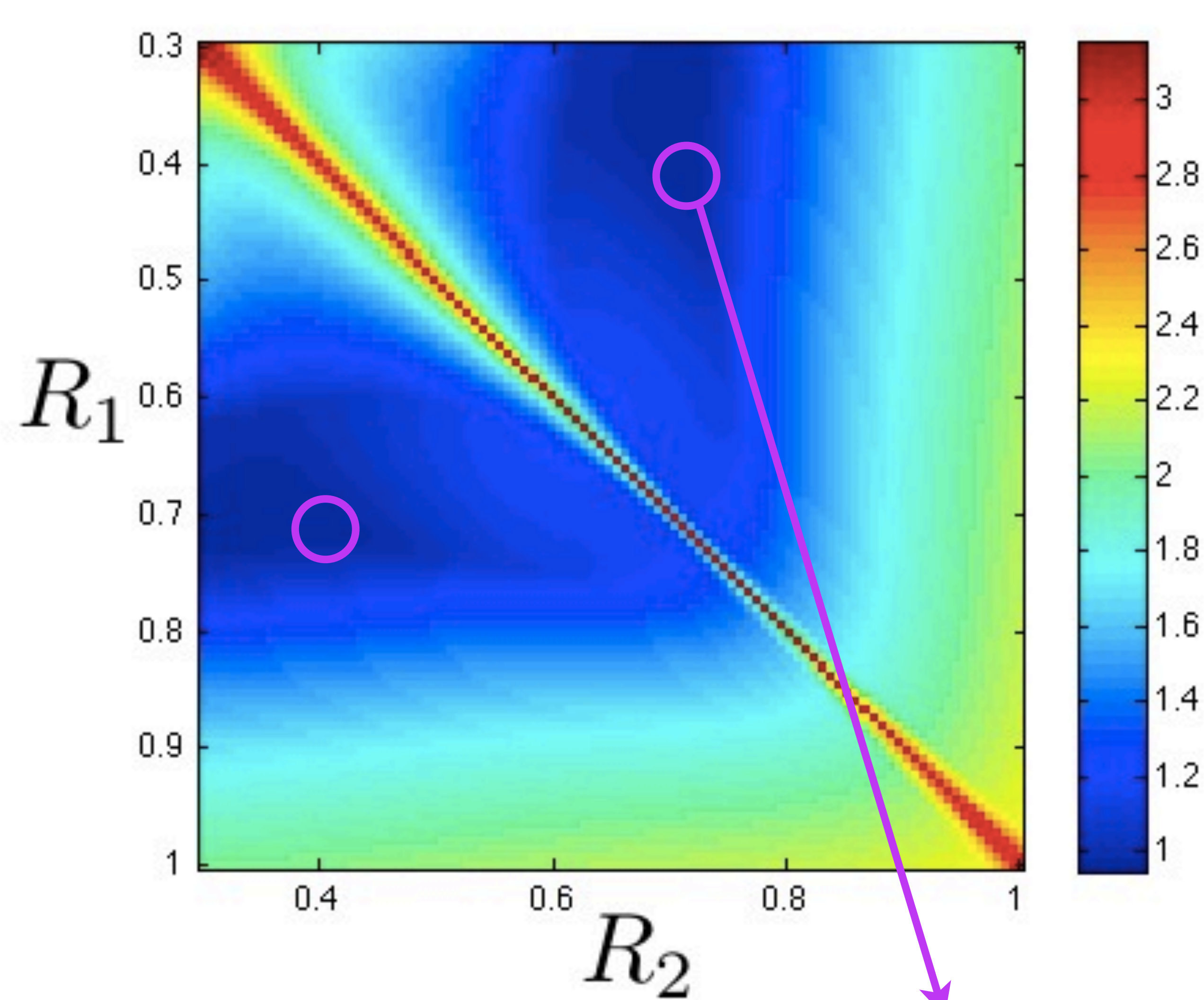


Optimizing probe configuration

The condition number can be used as a metric for optimizing probe configuration

8 probe points:





$$[R_1, R_2] = [0.41, 0.71]$$

Summary

- We have proposed a method for testing the aberrations in an optical system by measuring localized curvature variations
- Curvature is calculated by measuring the focus shifts in specific locations across the pupil
- The focus sensor working principle is based on a grating-on-grating contrast monitor, where the combination of gratings must suppress higher harmonics.
- Numerical simulations have shown accuracy below $\lambda_{EUV}/100$.
- Strategies are developed for optimizing probe locations for numerical stability

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